LOUISIANA STATE UNIVERSITY

Overcoming Environmental and Metal Interference using RFID Part 2

Final Project Report

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Abstract

Continuing the work of the 2010 Capstone Group, this project is intended to fully design and implement a prototype RFID system to simplify oil valve tree inventory management for Cameron International. The paper below is a discussion of the construction and testing of the designs presented in the preliminary design review. It will cover process, success, failure, and improvements that can be made towards the overarching goal.

For the sake of organization, this paper has been divided into two parts. Each will summarize one of the two main project goals for this 2011 Capstone Series: the Wake-Up Circuit and all related components and the Augmented Reality System. Both sections will act as chapters in the overall volume of our Final Design Review research paper. As the two concepts are independent in both research and decision-making, it has been decided that each section will contain its own table of contents; mini-introduction; numbering system for pages, figures, and tables; and its own conclusion. However, the entire document will share an overall introduction; project statement; project requirements list; citations page; and appendix which cover the two sections as a whole.

Introduction

This document is a formal report for the Cameron Project as part of the Capstone final design review. The goal of this text is to describe the requirements for the project, the methodology for testing a design concept, a description and analysis of the construction and testing process, a description of each component of each of the designs, and recommendations for improvements to the project for future implementations.

Team Cameron continued work from Team RFID's 2010 Capstone series, in which they developed an active RFID tag system that operates in harsh conditions for inventory management and maintenance of oil valve trees. The overall goal of the project through both semesters is to provide a working system that allows field technicians to read the IDs of each valve from the ground level and eventually interact with the company's database to acquire past records for the valves themselves.

Cameron would like to use the existing active RFID system in conjunction with an augmented reality display system. Thus, the project aims, as a whole, to improve upon and repair all existing conditions and issues with the existing active RFID system and to implement the desired augmented reality display system. These two concepts will be addressed in the sections to follow.

Project Statement

As mentioned before, in this 2011 Capstone series, Team Cameron aims to resolve some issues from the previously designed system as well as implement the remaining components necessary for a fully operable system. A method of putting active RFID tags to sleep and waking them remotely must be tested to solve the power consumption problems of the current system. Without a power management system, hereafter called a wake-up circuit, the lifespan of the tags will be reduced well below acceptable levels. This circuit must be designed to fit within the specified size of the tags without disrupting the functional RF system from the 2010 Capstone series.

The second focus of this project will be to develop and test, from ground-up, an augmented reality system that can be used in conjunction with a database to provide an efficient and convenient means of managing Cameron's oil well tree inventory. The system must be intuitive in order to inconvenience the field technicians as little as possible while streamlining the entire methodology of managing inventory.

Each of these project goals will be discussed more thoroughly in their respective design sections.

Project Requirements

The requirements listed in Table 1 were given to our predecessors upon beginning this project in the 2010 Capstone Series. These requirements detailed the desired functionality of the active RFID tags and reader. Our project will be using a functioning prototype developed by the previous team, which meets all of these requirements. However, we must be sure that any hardware modifications made to the existing network will not cause the system to fail to meet any of these requirements. As our system is building upon that of the previous group, we must ensure that no harm is done to the functionality of the system. Thus these specifications are important to the behavior of our project as well.

Table 1: Specifications for Previous Group

Requirement	Minimum	Ideal
Range of RF Tags	5 ft	20 ft
Life Span	5 years	20 years
Dimensions	8x8 in^2	2x2 in^2
Reliability	Every try	Every try
Production	5 years	3 years
Legal	Yes	Yes
FCC Compliant	Yes	Yes

The addition of the wake-up circuit will likely increase the size of each individual tag, in addition to increasing the lifespan. The choice of reader type and augmented reality display will engender a new requirement of system portability. Thus, the requirements for the 2011 Capstone series are different from those listed in **Table 1**. The table below lists our project's unambiguous specifications by decreasing importance.

Table 2: Specifications for Our Group

Requirement	Minimum	Ideal
Lifespan	5 years	20 years
Legal	Yes	Yes
Portability/Scalability	Yes	Yes
Robustness	Yes	Yes
Dimensions	8x8”	2x2”
Production	5 years	3 years
Range of RF Tags	5’	20’
Reliability	Every Try	Every Try
FCC Compliant	Yes	Yes

Lifespan has been denoted the most important specification to observe, as it has a large impact upon the robustness of the device. The wake-up circuit will drastically affect the lifespan of the device through addition of powered components, thus, finding the most energy efficient solution is vital. The system developed by the 2010 Capstone Group, which cannot utilize the built-in sleep mode, has a battery life of less than one month.

Legality is the next major specification. Cameron is interested in implementing a reader that is easy to use for a technician, which implies some sort of GUI interface. Cameron is interested in patenting our designs and eventually marketing them. This will not be possible if it encroaches upon another company’s intellectual property. Thus we must make sure that at all steps in our process legality is met.

The patent on our design will come before production, and thus Cameron is most interested in obtaining proof-of-concept from our project. Our prototype does not have to fit precisely within the specified dimensions, but it must remain easily transportable. However, future senior design teams *must* be able to scale the project down to the minimum. **Dimension** therefore remains an important specification, especially in regards to **portability**. In addition, the reader and augmented reality display system must remain capable of being carried by a single technician. Without this specification, any system designed will be of less service than intended.

Robustness is one of the major specifications of the project as it was the reason Cameron approached LSU with this project initially. The previous group has managed the most challenging aspect of this specification through successful implementation of an RF Tag system. However, any new components that are added must also be able to perform robustly in changing temperatures, mud, and other environmental concerns. This is of particular concern to the wake-up circuit, which will be included with the tags, but not the reader system, which will reside with a mobile technician.

The eventual aim of this design is **production**, but we will not be involved in such an endeavor, so it remains a low priority. Essentially, our results must be reproducible and relatively inexpensive. The other three specifications—**range**, **reliability**, and **FCC compliance**—depend specifically on the RF Tags and network design chosen, which has already been met by the previous group. However, they remain important to consider. Any alternative tags or a difference in chosen reader will, by market necessity, already be FCC compliant. The only part of the system that could potentially be non-compliant is the wake-up circuit; however, it depends directly upon choice of reader implementation, and so any design will reflect the FCC compliance of the reader.

Table 3: Specifications Prioritized Graphically

Priority				
CRITICAL	Lifespan	Legality	Scalability/Portability	Robustness
MODERATE	Dimensions	Production	Ease of Use	
LOWEST	Range	Reliability	FCC Compliance	Cost

In addition to the specifications mentioned in Tables 2 and 3, there are further specifications dependent upon the method chosen to implement the graphical user interface (GUI) for the active RFID tag reader. The reader/GUI will be mentioned in the following sections; however, requirements will be listed here for documentation purposes.

The major implementation includes a feature called "augmented reality". This feature describes the ability of a technician to view live video of the site, where the designed program would overlay the RF tag labels upon the specific valve it relates to on the oil tree. This definition of the feature dictates certain restrictions on the type of device it is implemented on. Such a device will require the capacity to display and capture live video feed, which necessitates the presence of a **camera** and a relatively large **color display screen**.

In addition to the hardware requirements of any device that will be used to display augmented reality, the program itself requires a specific environment for execution. The choice of **coding language** dictates the necessary device to run the program to implement augmented reality. This specific device that hosts the program will draw upon a maintained database of information to accurately draw the tags. Thus, the device must either have a significant portion of memory in which the—constantly updated—database is contained, or must have constant access to an online database. **Constant database access** is an important program requirement, and necessarily dictates the choice of device.

From a purely software execution standpoint, **accuracy of the program** in reading the picture and interpreting it in relation to the location information is essential. The augmented reality program would be worse than useless if it maps the location of the tags hundreds of feet from their actual location. However, the program does not have to be so accurate that one could perform surgery with it. The intent of the augmented reality is to ease inventory management, and thus there is an acceptable margin of error.

Table 4: Additional Specifications for Reader/Display System

Requirement	Minimum	Ideal
Camera	Yes	Yes
Display Screen	Yes	Color
Coding Language		
Database Access	Yes	Yes
Accuracy of Program		
Reliability	Every Try	Every Try

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Final Design Review Part 1

Wake-Up Circuit

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Introduction

The Wake-Up Circuit portion of the project is defined as a power management solution to increase the lifespan of the active tags beyond their current limit. While a basic design was compiled in the preliminary design review, it is the purpose of this report to discuss the testing and implementation of the design. Please refer to the preliminary design review for all research and methodology behind the design choices; this paper will focus specifically upon construction of a prototype. Any issues or changes to the design caused by this secondary development phase are of important value to the overall completion of the project, and to any future iteration.

This paper will focus upon implementation and discussion of our design in specific relation to the most important goals of this portion of the project: namely, lifespan and dimension. Though there are many other pieces included in a complete design, the intensity of the project necessitated concentration upon certain elements. Any research or design that has not changed from the 2010 Capstone Group's final design will not be touched upon in this paper. Any design elements from the 2011 preliminary design that have not been experimented with or changed will be touched upon lightly in the final schematic. Tests that are relevant to a final schematic are included. To obtain a more complete picture of the paths taken that did not directly result in a final schematic, please refer to the appropriate notebooks and milestone papers.

General Theoretical Design

Basic Overview

In order to extend the lifespan of the RF Tags to 3-5 years we will completely turn the power to the tag off while it is not being used. In order to turn the tag on we will then need to implement a wake-up circuit. This circuit will turn on the power to the tag after it receives the correct signal input, and turn the tag back off after a set amount of time. The tag will also ignore any signals received for a different amount of time, to prevent any tags that turned on late from causing an endless loop.

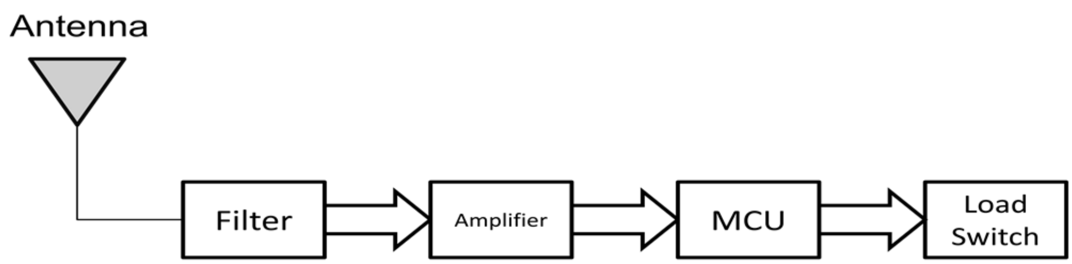


Figure 1: Wake-Up Circuit Diagram

The basic design of the wake-up circuit from the preliminary design report remains intact. An antenna receives an electromagnetic wave signal and converts it into voltage and current. The filter narrows down any converted signals received, looking for a specific frequency broadcast. An amplifier increases the voltage or current received through the antenna, which signals the microcontroller. The microcontroller has a preprogrammed set of instructions to execute upon a received signal, the most important of which is to turn on and off the load switch on a preprogrammed cycle. The load switch is placed to control whether or not power flows to the active tag.

Limitations on Hardware Implementation

Due to the considerable size of this project, the desire to have a working prototype at the end, and the decrease in available time, the students decided that immediately some design decisions would need to be minimized. In instances where it was available, the students used already constructed and purchased hardware in place of specific preliminary designs. This allowed the students to begin immediate testing and implementation, and to focus upon design refinement of the other parts. The immediate commencement of testing also allows for many of the assumptions made in the preliminary design to be verified or refined. Since there were a lot of assumptions made in the last design, this is crucial to construction of a working prototype. Discussed below are the specific limitations and construction decisions made by the students for the Wake-Up Circuit.

Antenna

The 2010 Capstone Group obtained a development kit from Texas Instruments that included 12 antennas. However, nowhere in the documentation does TI identify any information about them except that they are antennas. However, these antennas could be assumed to be designed for 2.4GHz applications, as this is the frequency that the tags are specifically designed for. Thus, the students decided to try to pin down the exact model and datasheet of the included antennas. Using the brand name printed on the antennas, the physical appearance, and the logical assumption of frequency operation, the students were eventually able to track down the model.

Figure 2: Antenova Titanis 2.4GHz Antenna

The included antenna is an Antenova Titanis 2.4GHz swivel. This antenna has a matched, 50Ω SMA connector, is designed for the 2.4GHz range, has linear polarization, and a good operating temperature range. It is a half-wave dipole antenna that averages 80% efficiency. Despite the fact that it is not technically meant for outdoors work, this is a relatively well-suited antenna to run our amplifier tests with. Though the original design plan called for a monopole antenna, the change to a dipole would not be disastrous. A monopole antenna is a better choice for power transfer between the reader and tag, but creates problems relating to grounding and matching. A dipole antenna is much easier to match and predict, but has lower power transfer characteristics.

Thus, since we already possess a significant number of the Titanis antennas, and have a detailed datasheet of their characteristics, we will use these for our tests and design. In addition, these antennas are relatively cheap and easy to purchase. Their inclusion in any final schematic would certainly not be a hardship.

Filter

Though the designed Chebyshev mentioned in the introduction has desirable outputs, there were several undesirable details about the design. Despite multiple attempts, the students were unable to physically design a filter that used higher values of capacitors and inductors. The values specified are miniscule, at best, and hard to solder. It is almost not worth the effort, especially when other options are easily available, or on hand.

These include surface-acoustic wave devices that are already available to the department. These devices are abbreviated as SAW filters, and function in much the same way the Chebyshev filter does. They read an incoming signal and only let a signal with the desired frequency through, preferably with minimum attenuation. Where they differ is the method in which this is accomplished. While Chebyshev filters rely upon a combination of capacitors and inductors in a specific format, SAW filters change electrical inputs into mechanical signals through the use of piezoelectric materials. The filter will only resonate when a certain frequency signal is input, predicating its use as a filter. In addition, they are often balanced to a 50Ω line, much as the one that the antenna is based upon.

The SAW filters available to the students are already constructed and balanced, ready for testing, and operable at 2.4GHz. They are produced by a company called SAWtek, with detailed datasheets included. Thus, instead of waiting for delivery of components and the impractical construction requirements, the students will experiment and test the three filters to determine the best one.

Amplifier

Early on in the semester, there were major difficulties in accurate simulation of the amplifier circuit. The version of SPICE available to the students behaved strangely at ultra high frequencies, in direct contrast to the prediction of the equations used to design a basic amplifier. The weight of colloquial evidence was also strongly behind the students; several papers involving different implementation of this circuit at high frequencies exist, such as the paper by Cho, Hong, and Kim. Each of those projects worked, though they have differences compared to the goals of this project. In addition, time was running out, and construction had to begin; there would already be a delay while waiting for the parts to arrive. Thus, the students decided to believe the set equations had at least a basis in reality.

EQ 1: $$V_{out} = 2*N*V_{pk} - V_{drop}$$

EQ 2: $$V_{drop} = [I_{load}/(6*f*C)]*(N^3 + 2N)$$

All components capable of performance at ultra high frequencies are usually small and contained in surface mount packages. These packages can range from a size of 2920 (0.29 x 0.2”) to 01005 (0.016 x 0.008”). Due to the limitations of our soldering experience and equipment, the smallest possible size the students can build with is 0603, though 0805 is preferable. These components are too large to work at 2.4GHz frequencies due to parasitic capacitance, and the students did not have the time or money to send the circuit off for professional assembly. The 0603 components are tiny enough that a magnifying glass is already required; special machinery and techniques would be required to solder the components small enough to work at 2.4GHz.

Since Cameron is interested in a prototype, and open to the idea of using active tags at lower frequencies, it was decided to design and build an amplifier for the lower frequency of 900MHz. If the students can demonstrate that this type of circuit works at UHF, it is even more likely that a circuit built by professionals would work at the even higher frequencies of 2.4GHz.

To further decrease the amount of time required to construct the circuit, the students decided to home-etch a printed circuit board rather than send a schematic out to be professionally etched. Surface-mount components cannot be used in a breadboard, and professional etching can cost a lot and often takes more than a week. Learning to design a PCB schematic was already a difficult task with no known completion date; the students did not want to add to the delay already created by the continued simulation failures. Guides to home-etching PCBs are pretty specific that once a schematic is obtained, it only takes a few hours to produce a fully etched and soldered PCB.

This small turnaround time is ideal for the student's purposes. Since the plan is to build and test at least five different amplifier schematics, and then refine and rebuild from there, we can't afford any delays. The more testing that could be slotted into the rapidly disappearing time, the better the final prototype would be. The actual process of home-etching, as well as the difficulties inherent in designing a PCB for RF work, is discussed later.

Transistor

The amplifier design included a transistor that would act as a switch; it would be triggered by the amplified signal, and in turn trigger the microcontroller to control the circuit. Since the choice of this component relies heavily upon the output from the amplifier, it was decided to leave this component out of consideration until a better idea of output could be obtained. If the amplifier could be tweaked to produce a high enough signal, then common, cheap transistors could be used. Otherwise, the lower the trigger signal, the more expensive the transistors would become. There is no use to buying a component we don't know if we can use.

Microcontroller

Figure 3 -- Atmega328P-PU

Originally we purchased 3 Atmega328PU-P micro controllers, as well as the AVR Dragon and STK600 starter kit. The Atmega328 micro controllers come standard from Atmel with AVR bootloader, therefore we needed to download an Integrated Development Environment (IDE) to interface with the micro controller. Atmel has free software called AVR Studio that is used to create, compile and debug code, and allow us to download our code straight onto the on-chip flash of the AVR micro controller. However after much time spent researching on how to use the AVR software and STK600 starter kit to program the MCU it was determined that it would be more efficient and straightforward to simply use a MCU that had the Arduino bootloader instead of AVR. We purchased an Arduino UNO from Radio Shack to test with our circuit. The Arduino UNO comes with a test board and Atmega328P-UP with the Arduino bootloader already on the micro controller. The testing of it will be discussed in a later section.

Battery

The batteries we have chosen are Lithium Thionyl Chloride AA batteries. These batteries were chosen because of their extremely low natural decay of less than 1% per year.

This battery also operates over a wide temperature range while maintaining an ample supply voltage of 3.6V and current capacity of 2400mAhr. Each individual battery has the specifications listed in the table below.

Table 1: Lithium Thionyl Chloride Battery Specifications

Lithium Thionyl Chloride (AA)	
Capacity	2400mAh
Voltage	3.6V
Current	100mA max
Temperature	-55° C - 85° C
Self Discharge	<1% Per Year

These ratings are more than high enough to power the tag for a significant period of time provided an adequate management solution is enacted. Generically, each battery has a chemical lifespan of 15-20 years. This individual lifespan combined with the low level of power decrease per year makes these ideal batteries. The temperature range is also highly advantageous. Most batteries suffer degradation of capacity at high temperatures. Fortunately, the material used to construct the case is well-suited to insulation at high temperatures. Therefore, this temperature range is complementary to our application. They are, unfortunately, rather expensive compared to normal alkaline AA batteries. This particular type of lithium battery costs about $7 each, although they can be bought wholesale for much cheaper. This tends to limit their use in civilian applications.

Physical Design

Signal Performance

The focus of this project depends heavily upon the production and performance of high frequency signals in multiple mediums. The received signal directly powers the wake-up circuit, and the entire system must work from a certain difference despite metal interference. Thus, it is logically sound to closely analyze and test the signal performance of various parts of the circuit. Due to the staggered reception of parts and certain hardware and time limitations, most of the tests concerning signal performance were run at 2.4GHz. Often these tests were intended to recreate or verify datasheet and research information. Thus, if we choose to use the system at 900MHz, we can assume any tests run at that frequency with that equipment will also follow the technical data available.

Antenna

The students decided to test the Antenova Titanis 2.4GHz Antenna on the Network Analyzer, which is a machine that measures the network parameters of circuits. In our case, we want to look at the s-parameters, or the reflection and transmission behavior of the antenna at radio frequencies. Of specific interest to measure is a parameter known as S_{11}, which reads the reflection of an input signal at the input port. Essentially, an input signal is run through the device, reflected back from the end, and it is this reflection that an S_{11} characteristic reads.

Antennas broadcast at the same frequency they receive at, therefore the lowest point on an S_{11} characteristic is the frequency the antenna is designed for.

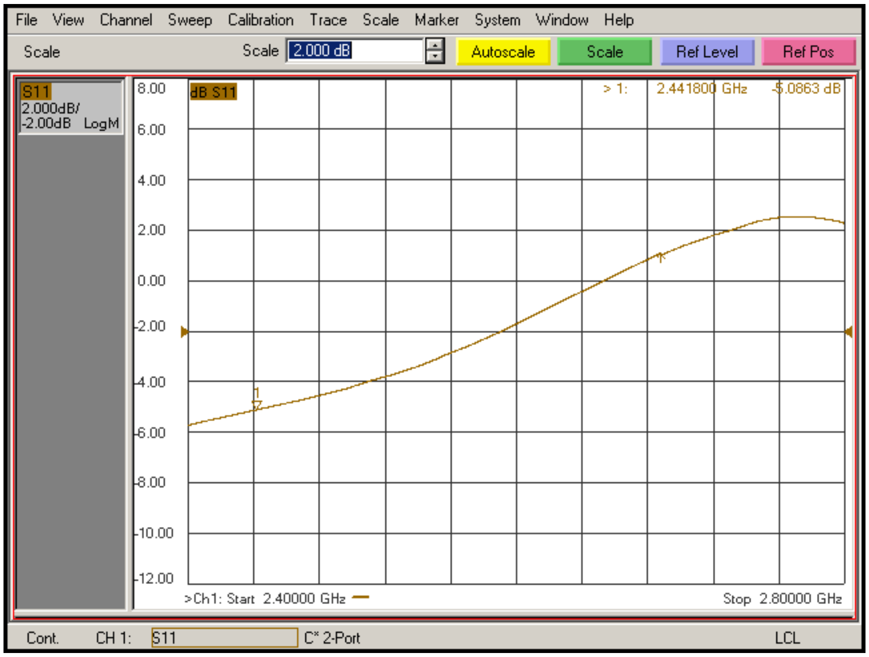


Figure 4 -- Antenova Titanis S11 Characteristic

Though this characteristic is zoomed in quite far, it is obvious that the lowest point lays right around 2.4GHz. Of note is that no antenna works at a singular frequency; they all have reception and transmission around a range of frequencies. The more narrowly the antenna is designed, the smaller the range of frequencies. Some antennas are even designed to work at multiple ranges; our research turned up several antennas that worked at both 900MHz and 2.4GHz.

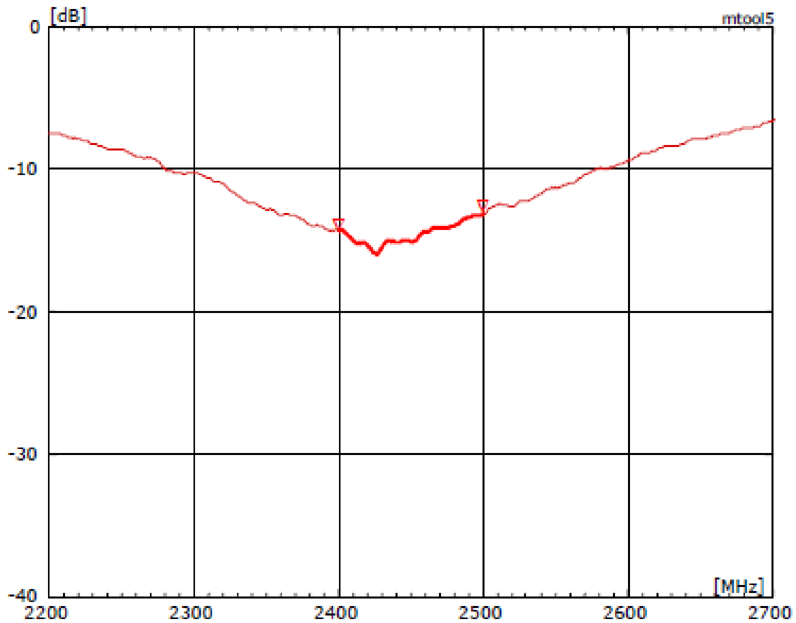


Figure 5 – Datasheet Return Loss of Antenova Titanis

The figure above is obtained from the manufacturer's datasheet for the Titanis 2.4GHz. It describes the expected return loss, which is a figure used to measure the amount of signal power lost by premature reflection due to mismatches. For instance, if there is a mismatched load, or the transmission line is too sharp, power will be reflected back earlier than it should be. Return loss is equivalent to the s-parameter S_{11}, as it measures the total reflected power over the total incident power, as displayed in the equation below.

EQ 3: $$RL'(dB) = 10\log_{10}(P_r/P_i)$$

When comparing **Figure 4** and **Figure 5**, it is immediately obvious that the loss measured on the network analyzer is much less than the loss reported by the datasheet. The network analyzer shows around -6dB loss, while the datasheet reports we should expect closer to -15dB loss for the same frequency. While this is not exactly a desirable effect, it is also not a complete deal breaker on use of the antenna, either. This decibel difference could be caused by a multitude of things, including individual differences in antenna construction per batch or mismatch with the network analyzer available to the students. It is the students' belief that these antennas are good choices for use in our circuit.

Filters

There are three SAWtek filters available to the students, which unfortunately have no better names than serial numbers: the 856435, the 855916, and the 856539. All three filter at 2.4GHz, although there are multiple other characteristics that distinguish them. Most of our tests were conducted with the 855916 filter, which has a single 50Ω output that does not require matching. The loss in signal caused by transmission through the filter, known as insertion loss, can be anywhere from 2.5-5dB, a very low level.

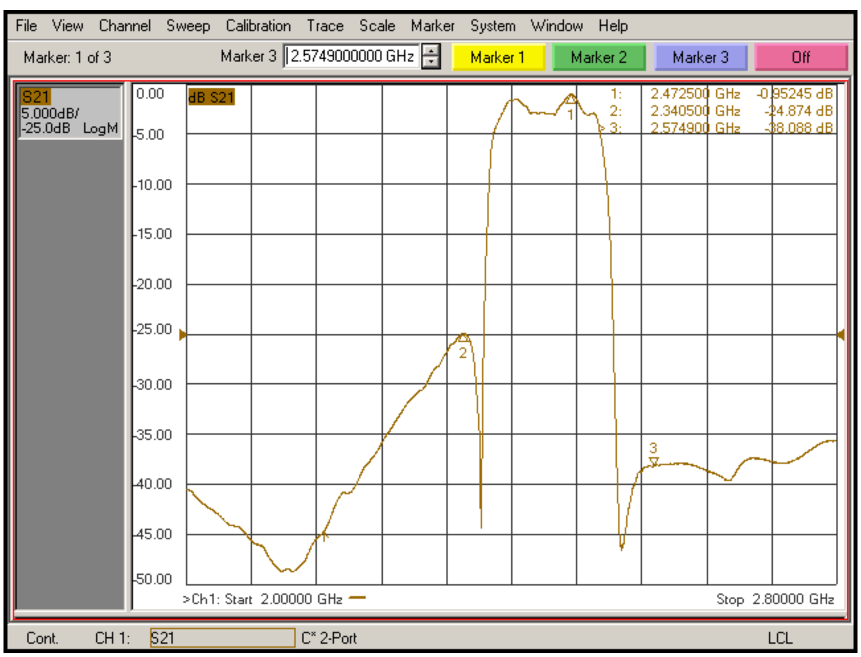


Figure 6 -- 855916 S21 Characteristic

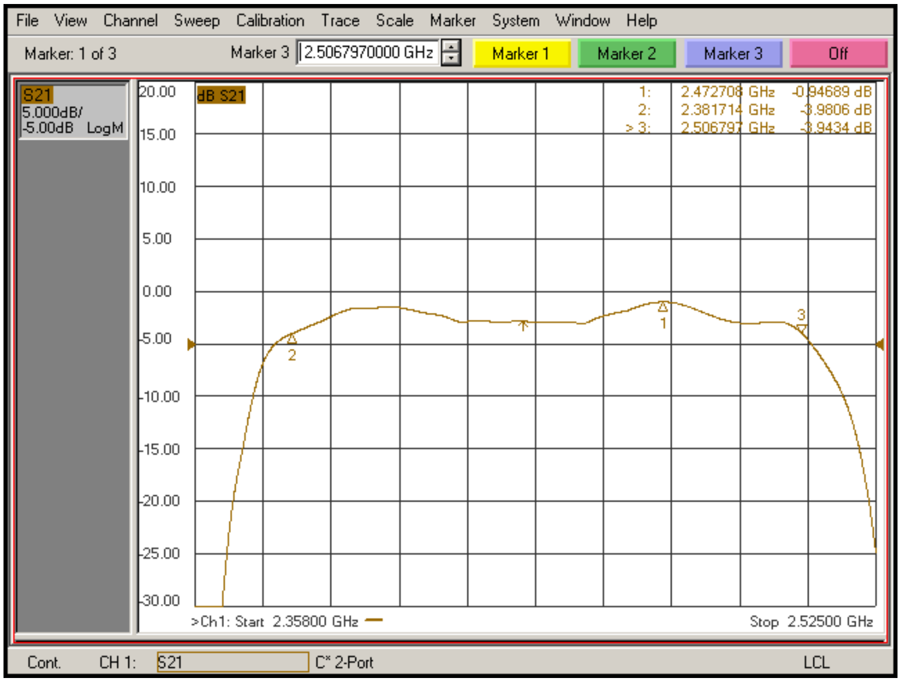


Figure 7 -- 855916 S21 Characteristic Zoom

The figures above describe the S_{21} characteristic of the filter as measured on the network analyzer. Similar to insertion loss, it measures the power transmitted at the input port over the power measured at the output port, after the signal has travelled through the device.

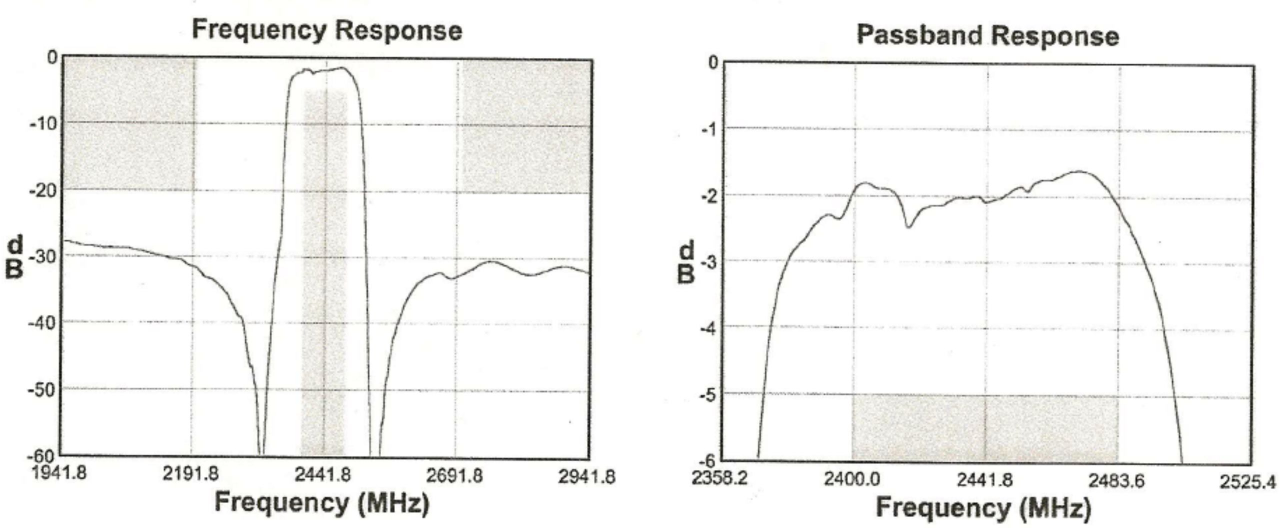


Figure 8 – 855916 S21 Datasheet Characteristic

The figure above represents the same images in **Figure 6** and **Figure 7**, but this time obtained from the datasheet provided by the manufacturer. **Figure 6** is comparable to the Frequency Response figure on the left in **Figure 8**. Though the network analyzer shows a spike before the attenuation drops to zero, this is still well below levels that would change the operation of the filter. The close-up of the frequency response of **Figure 7**, also known as the Passband Response in **Figure 8**, is used to determine the amount of insertion loss caused by the filter. In a perfect world, the passband would top out at 0dB, or no loss. The datasheet shows that we can expect around 2dB of loss. The network analyzer confirms this; never does the loss hit the maximum expected of 5dB. This is an exceptional performance, and definitely matches with the datasheet.

Combination Performance

Since both the filter and the antenna were present for the network analyzer tests, it was decided to test their behavior together. In a wake-up circuit, the antenna would be connected directly to the filter, which would then be connected to the amplifier. Unfortunately, there is no way to test this forward momentum on a network analyzer; an antenna only has one SMA connector, thus all tests on it necessarily must be S_{11} characteristics. Thus, the 855916 is connected directly to the network analyzer, and the antenna connected to the filter. An S_{11} characteristic is taken; this particular signal must flow through both the filter and the antenna and then back to the input port again.

Like the S_{11} characteristic taken purely with the antenna, we can expect that the point of most loss will reflect the signal that was broadcasted by the antenna. Unfortunately, due to the signal travelling twice through the filter, we can expect two times the normal amount of insertion loss. This will leave the basic rejected or unfiltered signal not at 0dB, but at -5dB.

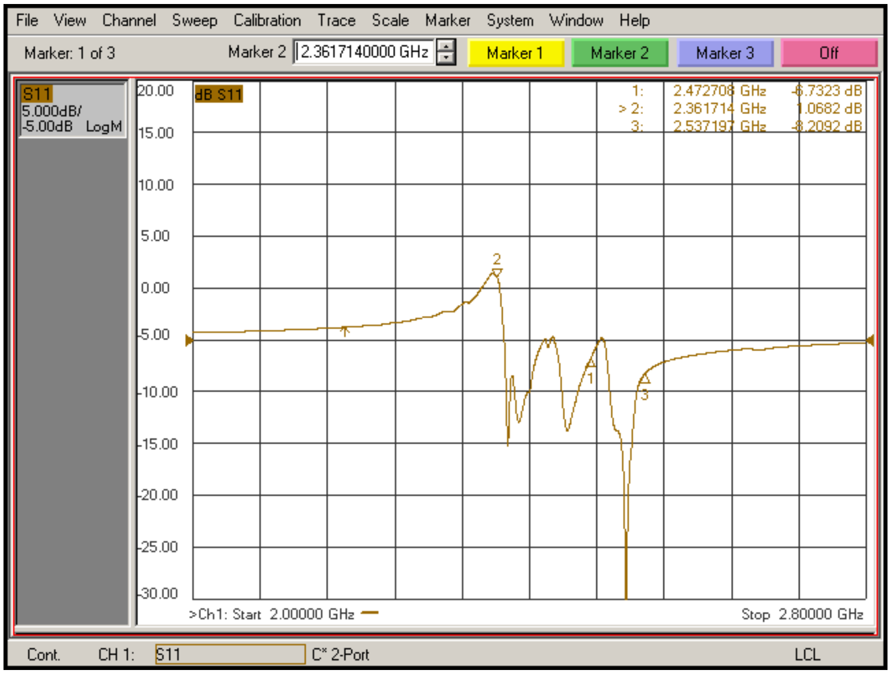


Figure 9 -- Antenna + 855916 S11 Characteristic

This result from the network analyzer is exactly what we would expect from the logical outcomes. Filters, like antennas, have a range that they allow to pass through, which explains the range from 2.36-2.54GHz in which there is signal passage. Once the signal moves outside of the acceptable range for the filter, the rejection begins again and the signal approaches the expected 5dB loss.

The low dB modulation and loss is especially important to our circuit. The more powerful the signal that makes it to the amplifier, the less work the amplifier has to do to power a transistor. If the incoming signal is higher, we will need fewer stages in an amplifier to be effective, which helps the circuit to stay within the dimensional requirements. Though there are only examples of one SAW filter in this paper, all three filters present datasheets with low insertion loss.

System Transmission and Reception

The 2010 Capstone Group obtained a development kit from Texas Instruments that is vital in testing the system. This devkit includes two development boards, which, when two CC2431 tags are placed on top and turned on, can be used to measure transmission and reception of the system. By connecting the development boards to a computer by USB, and using the freeware RF Studio software provided by TI, it is possible to get RSSI readings from each tag. One tag can be set to transmit, and one tag can be set to receive, with multiple options for experimentation. The students decided to run various tests to verify the antenna research conducted last semester.

Test 1

The first test consisted of a general background and baseline readings. The two tags were placed immediately next to each other, with the antennas pointed straight up to the ceiling. One was set to transmit at 2405MHz at 0.2dBm, while the other was set to receive. The first iteration of Test 1 was intended to measure the amount of background noise reception by the receiving tag. The transmitter was not turned on for this iteration. The second iteration of Test 1 measured the reception by the receiving tag when the transmitter was on, and had been broadcasting for a while.

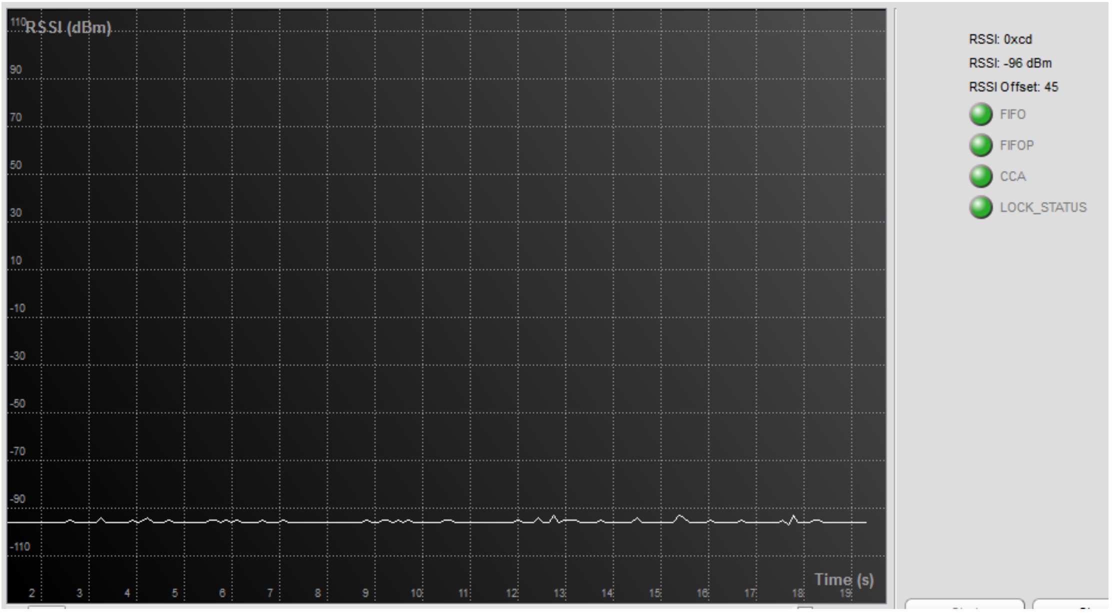


Figure 10 – Signal Measured by Receiving Tag, Test 1 Iteration 1

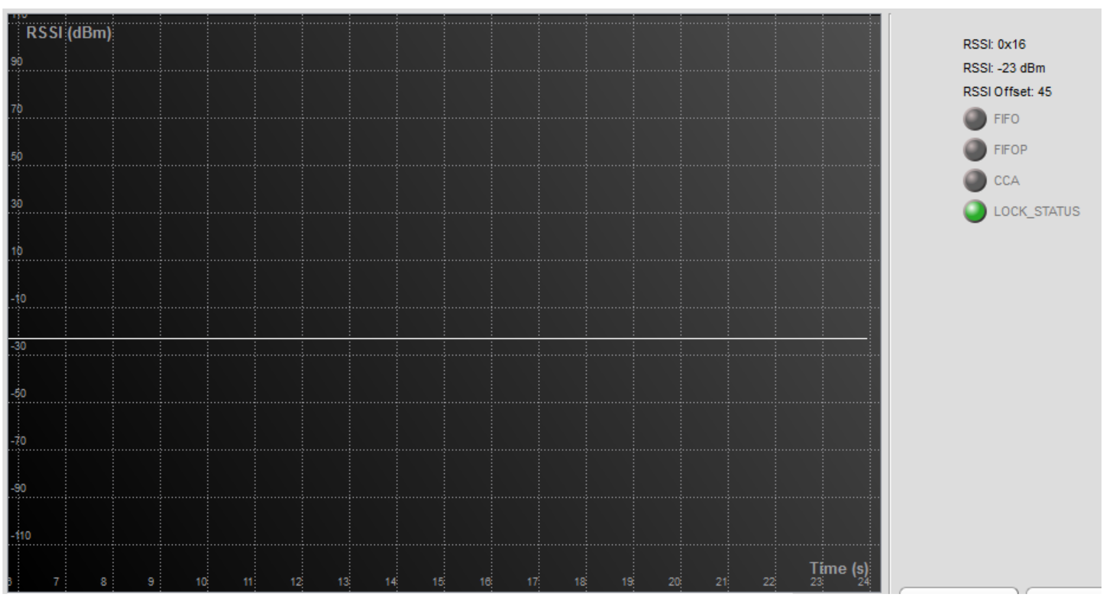


Figure 11 – Signal Measured by Receiving Tag, Test 1 Iteration 2

The background noise is as expected. The antenna's sensitivity is around -90dBm, and a signal reception of any kind was to be expected, as we conducted these tests in ERAD, a busy building with lots of interference. Even with the physical closeness of the tags, iteration 2 only had a reception of around -25dBm. This does not seem to hold up with the antenna's datasheet, or the tests conducted by the 2010 Capstone Group, in which the range of the antenna is stated to be at or around 15m. With a range like that, the antennas being this close together, one would expect a better reception. However, we have conclusively proved that the receiving tag does indeed register a difference when the transmitting tag is both on and off.

Test 2

For this test, the transmission settings were left the same as in Test 1. Both transmission and receiving tags will be on for this test. The only thing that will change is the distance between the two tags, which will not change much due to the necessity of leaving both tags connected to the computer. The distances involved in all tests are a few feet, max. To accurately measure the effect upon the received signal, the tags will begin in the original, adjacent position and be moved while the signal is transmitting.

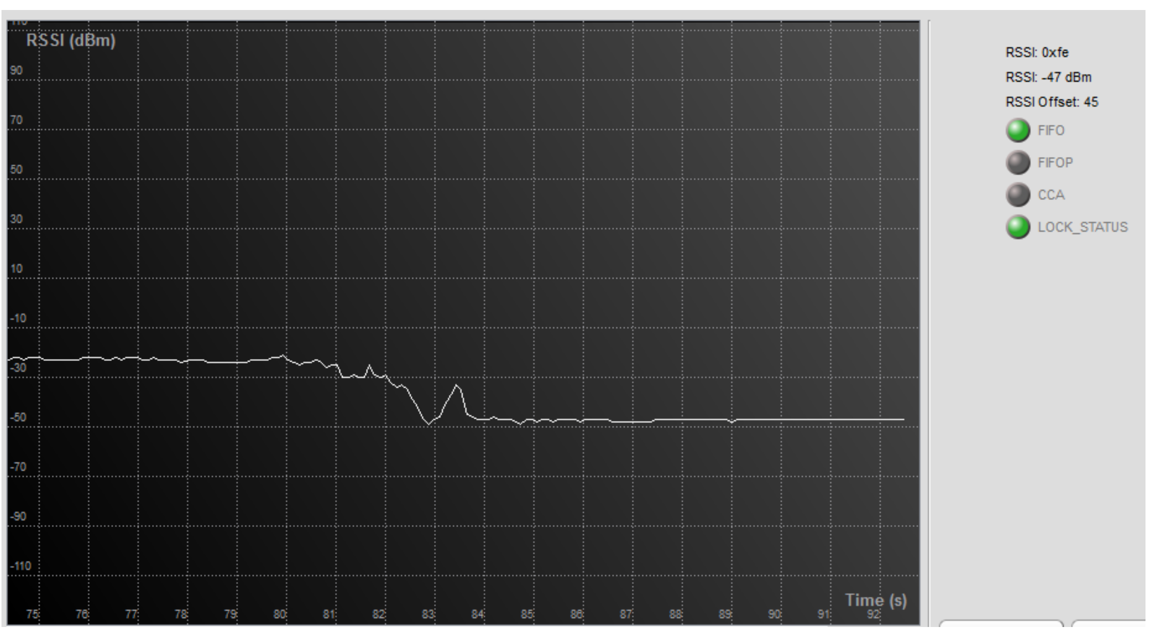


Figure 12 -- Signal Measured by Receiving Tag, Test 2

The disturbance in the middle of the measured signal is caused by the physical movement of the tags farther away from each other. The drop in received signal caused by this increase in difference is visible in the graph. The left side is when they were sitting close together; the right side demonstrates the settling of the signal after the tags had been moved. The signal difference is around 20dBm, a pretty significant drop caused by a slight distance moved. Again, the amount of drop seems odd given the distance results from the 2010 Capstone group, though the antenna research from last semester is pretty clear that we should expect at least some signal drop with increase in distance.

Test 3

This test is intended to measure how different transmission powers can affect the reception of the signal. Both tags are moved back next to each other in the same position as Test 1. Unfortunately, we cannot vary the transmission power in the midst of broadcasting, so we must turn off the transmitting tag and then turn it back on with the new power. This will create a blank spot in the middle of the received signal where the reception drops down to background noise levels. Iteration 1 begins at 0.6 dBm and drops to 0.2 dBm. Iteration 2 begins at 0.2 dBm and drops to -5.7 dBm. Iteration 3 begins at -5.7 dBm and drops to -25.2 dBm.

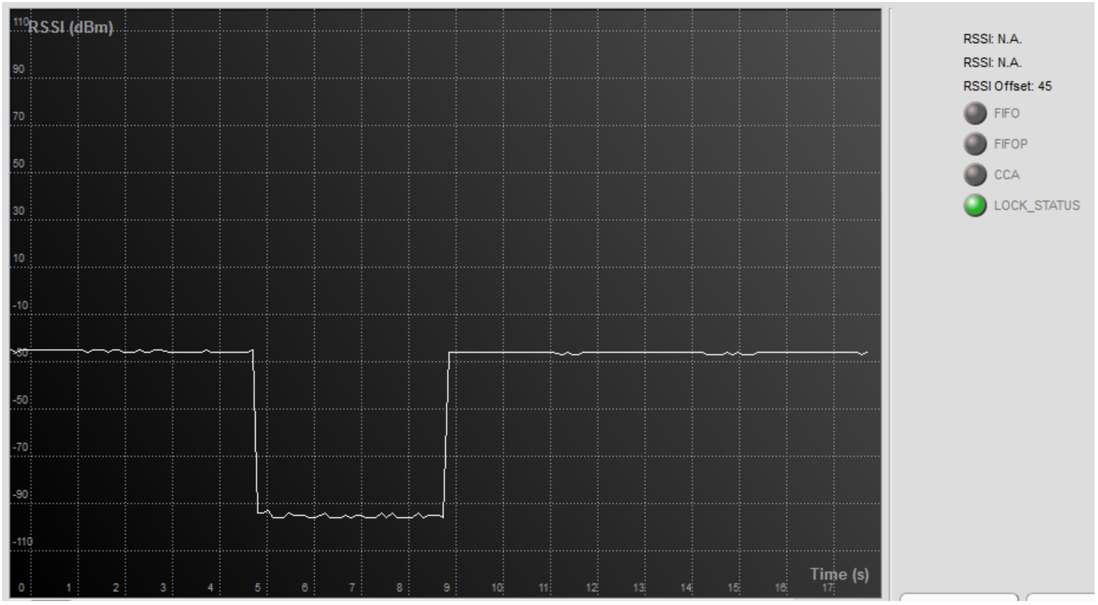


Figure 13 -- Signal Measured by Receiving Tag, Test 3 Iteration 1

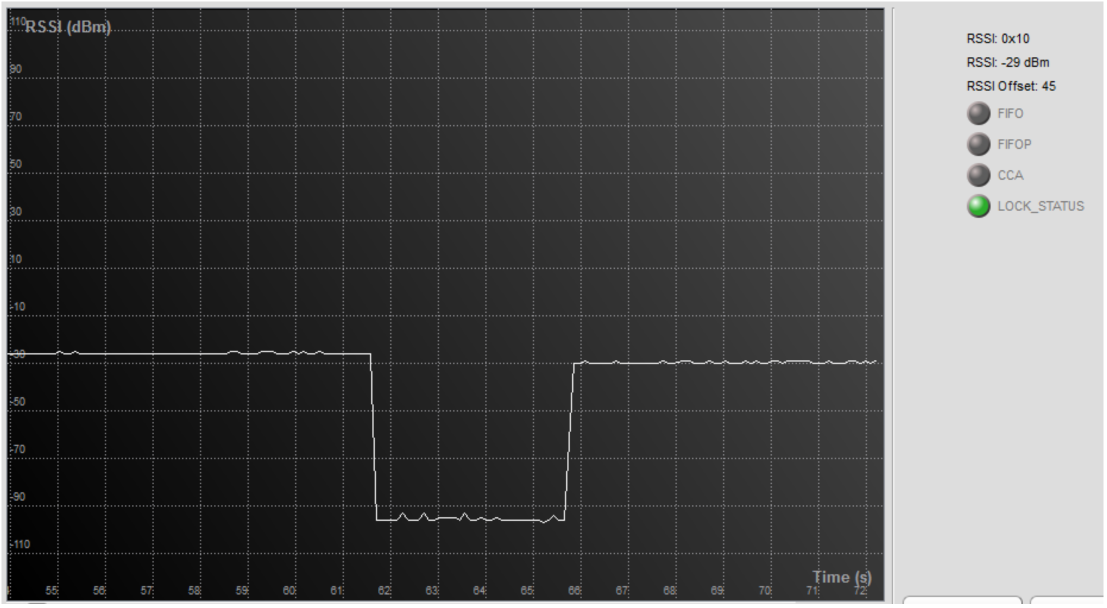


Figure 14 -- Signal Measured by Receiving Tag, Test 3 Iteration 2

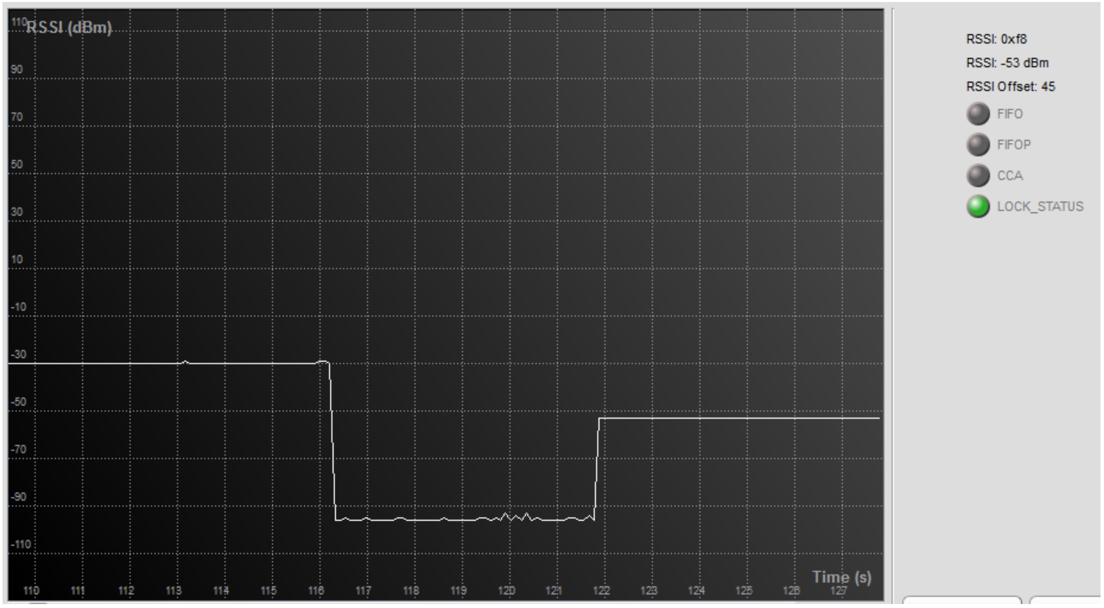


Figure 15 -- Signal Measured by Receiving Tag, Test 3 Iteration 3

The biggest measurable difference is visible in Iteration 3, which is understandable due to the greater difference between the two transmission powers. The first iteration has only a few tenths of power difference, while the second iteration has around a -6dBm difference. The third iteration, instead, has a -20dBm reference, so it makes sense that the reception difference would be more visible. These test results verify that the more power a "reader" can transmit with drastically affects signal power reception, even without any physical movement of the tags between tests.

Test 4

For this test, both tags remain adjacent to each other in the Test 1 position. Instead of varying the transmission power in this one, we will vary the reception frequency. This variance simulates a mismatch of sorts between antennas. Increasing the frequency changes the IEEE standard broadcast channel to different numbers. For similar reasons as Test 3, we cannot simply change the reception frequency during operation of the circuit. Therefore, assume that the transmitter is broadcasting normally as in Test 1, and compare all results in this test to that standard. In the first iteration, the reception frequency has been altered to 2410MHz, or channel 0x0C. In the second iteration, the reception frequency has been altered to 2480MHz, or channel 0x1A.

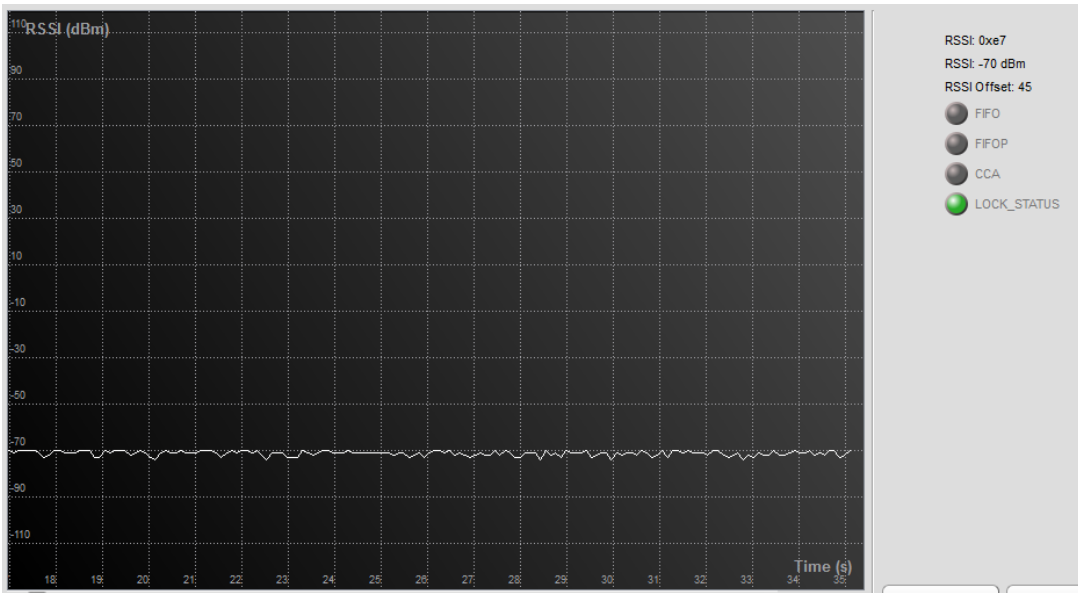


Figure 16 -- Signal Measured by Receiving Tag, Test 4 Iteration 1

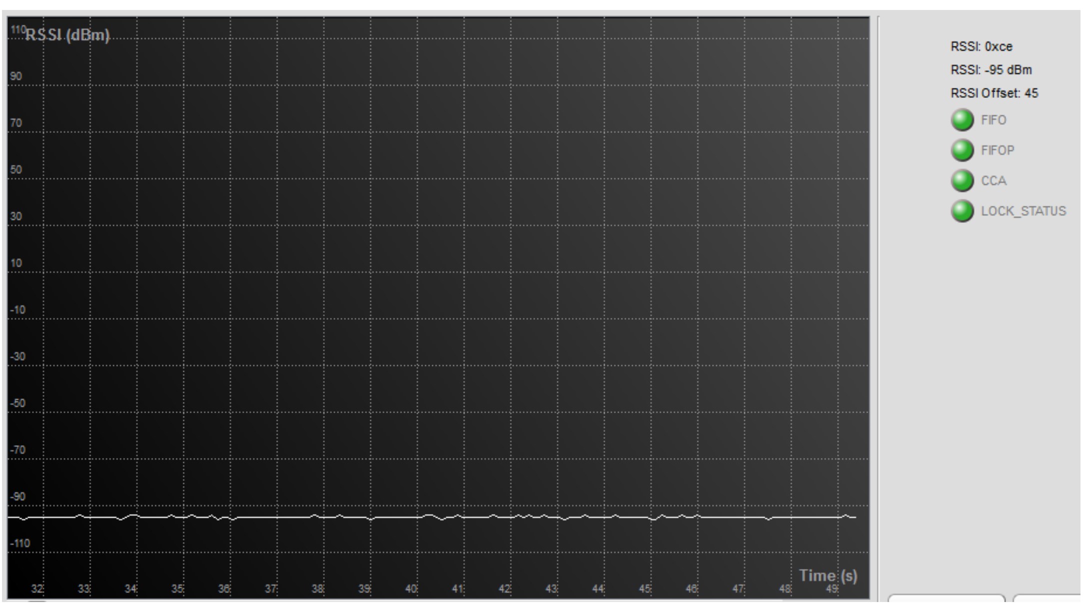


Figure 17 -- Signal Measured by Receiving Tag, Test 4 Iteration 2

Despite the close difference in frequency in iteration 1, there is still a significant drop in reception. Test 1 demonstrated that in this physical position, with all frequencies matching, we could expect around -23dBm reception. Iteration 1 has a drop to -70 dBm. This is a rather large drop. Iteration 2, in fact, might not even signal reception of a transmitted signal at all. The signal received is comparable to the general background noise. These results are to be expected considering antenna theory. Two antennas that are not on the same channel will not interact, although there will be occasional interference in the closer channels. This purpose is exactly why the channels were originally defined in the first place, to prevent wireless networks from interference with each other.

Test 5

In this test, the tags are moved back into their Test 2 position, aka a short distance apart. This test will simulate an object's interference with the received signal when placed directly between the two tags. The object will be placed in between the two tags while they are already in communication, slightly closer to the transmitter rather than the receiver.

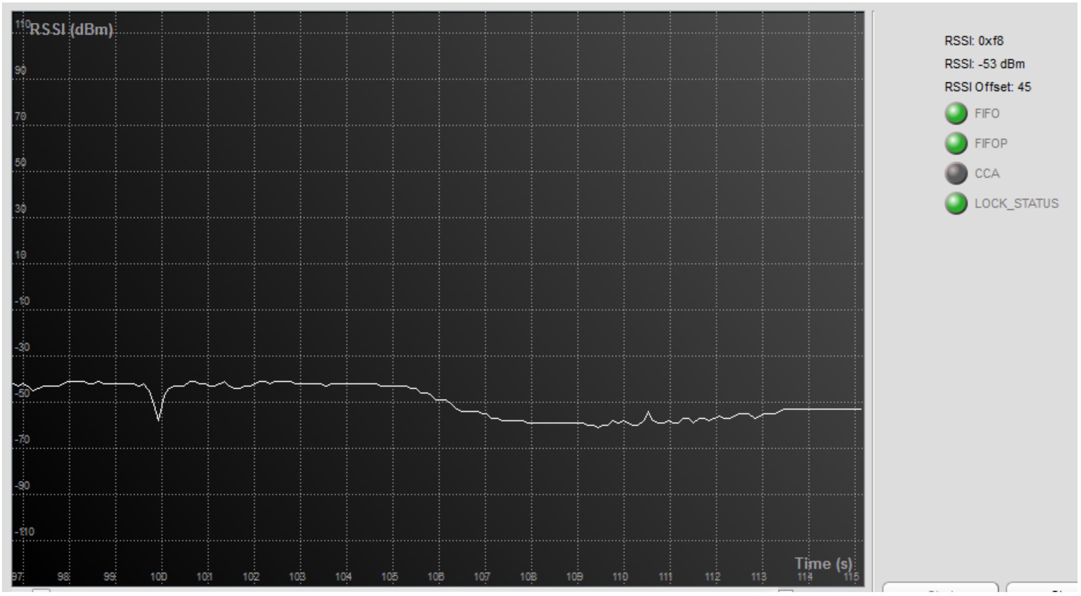


Figure 18 -- Signal Measured by Receiving Tag, Test 5

Though the drop in reception is not as noticeable as it is in many of the other tests, there is clearly a fall in the middle of the graph. Since these antennas broadcast in an omnidirectional pattern, a single object directly in the broadcast path will have only a moderate effect. We can imagine that reflections off of the nearby walls mitigated the effect at least a little. Therefore, it makes sense to eventually run tests with an enclosed case around the antenna to make sure there's no effect.

Test 6

In previous tests, the students were careful to keep the antennas in the same positions, regardless of the location of the tags. In this test, we will purposefully mismatch the positions of the antennas, and then rematch them in the midst of broadcasting. This will not require turning off the transmission at any point, as it involves movement of the physical antenna rather than manipulation of the settings within the program. The tags are placed in the same position as Test 1. The antenna on the transmitting tag is turned horizontal, or parallel with the board and ground. The antenna on the receiving tag is left vertical, or perpendicular to the ground. In the middle of transmission, the transmitting antenna is returned to vertical.

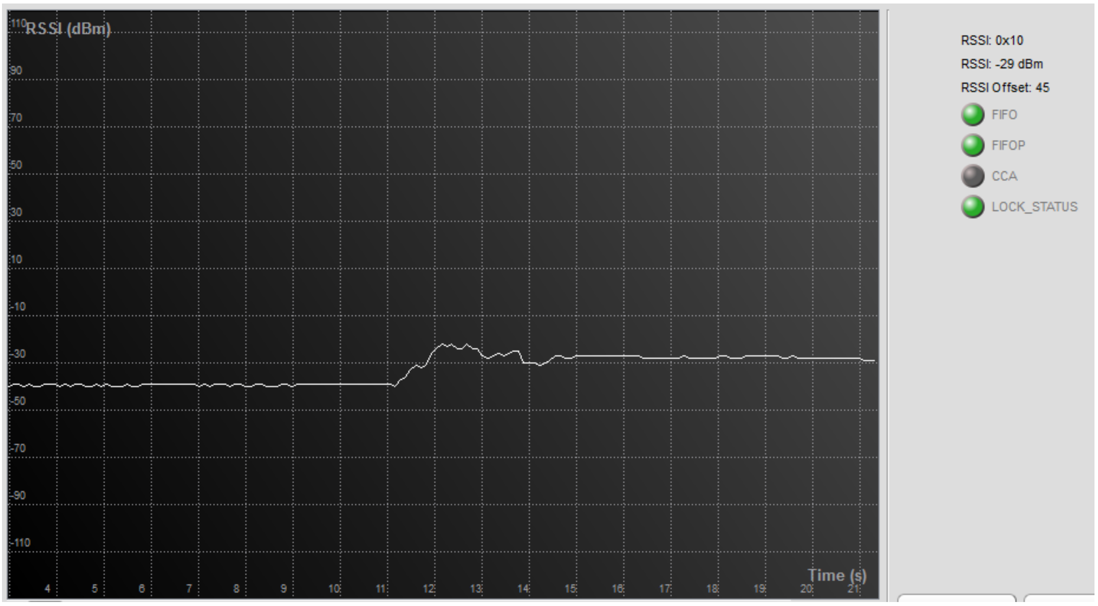


Figure 19 -- Signal Measured by Receiving Tag, Test 6

There is a measurable difference in signal reception between the two antennas when the positions are changed. The reception increases by around 10 dBm once the antennas are again matched, a pretty significant difference when dealing with the logarithmic decibels. The tags were not moved closer in any way to affect this result. These results make sense due to a property of antennas called polarization. This property is explained in detail in the preliminary design review; in summary, the physical position of the antenna affects the properties of the wave it broadcasts. If the polarization is not matched as well as possible, it strongly affects reception.

Z-Locator System

Attempts to replicate the z-locator data compiled by the 2010 Capstone Group were met with failure. Despite easy access to free software from TI meant to interact with the RF Tags, the students were unable to replicate results. To use the z-locator software, the tags must be connected to the computer both by USB and serially. Unfortunately, the computers originally available to the students did not have serial ports. An attempt was made to fix this issue with the purchase of a usb-serial cable. Despite considerable trouble-shooting by the students, and the computer's own recognition of the tag on the other end of the usb-serial cable, the software itself refused to acknowledge the connection. Attempts to use the lab computers to continue testing the z-locator system also failed to recognize the serial connection. Since the z-locator data is not exactly important to continuation of the wake-up circuit, we chose to leave it alone.

ABS Plastic Case Testing

The students obtained six quarter-inch thick pieces of ABS plastic. Using these pieces, it is possible to construct a very rough cubic case to contain a receiving RF Tag. The 2010 Capstone Group decided to use ABS plastic in their case because it is the material the 3D printer uses. Our preliminary design review decided to continue using this material because of its rugged temperature range and purported common usage in electrical applications. The material of the case is important, because to make the system more robust, we should not have any holes in the design. This means that the antenna will likely need to be contained within the case. Since our wake-up circuit depends so strongly upon signal reception, it behooves us to test the signal reception when surrounded by the case material. Thus, the students ran a test with the tags in the same location and same settings; but one test without the case (iteration 1), and one with a makeshift case (iteration 2).

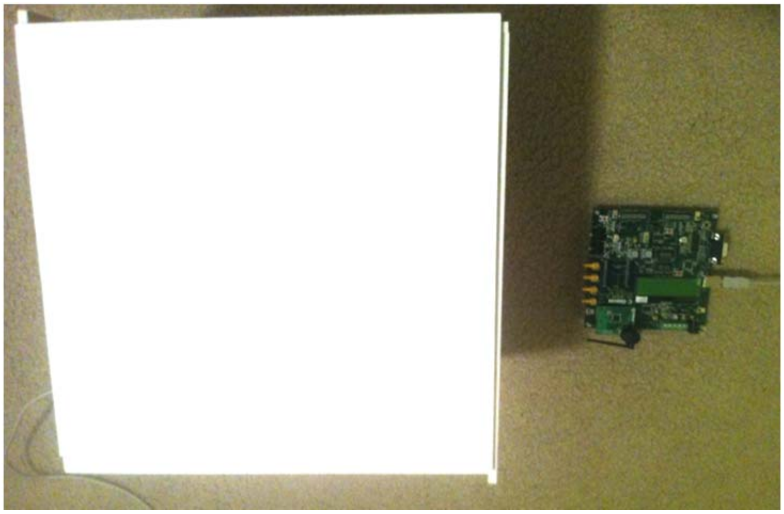


Figure 20 – Picture of Makeshift Case

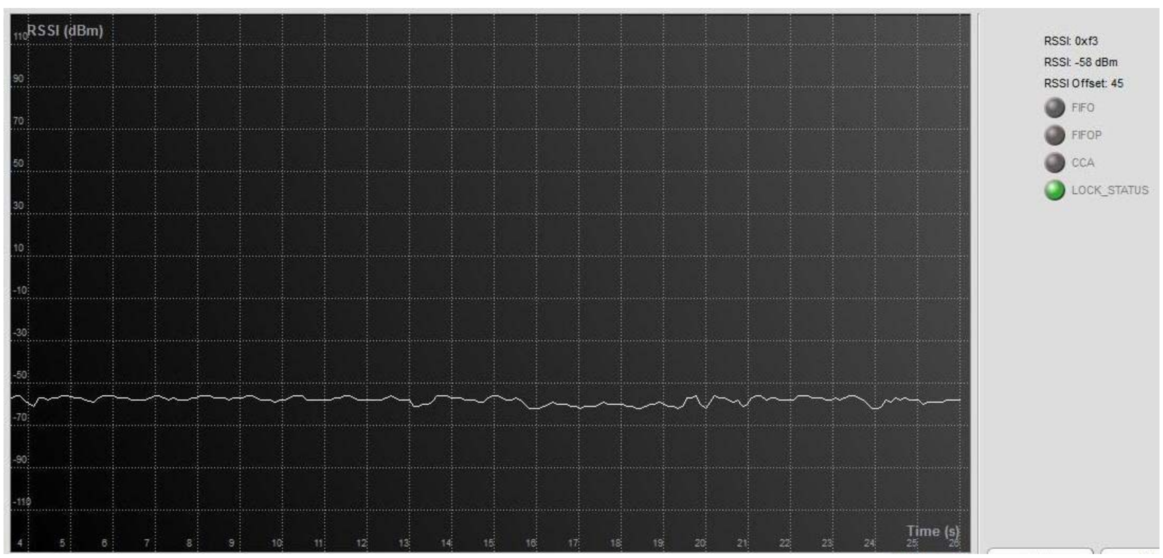


Figure 21 -- Signal Measured by Receiving Tag, Iteration 1

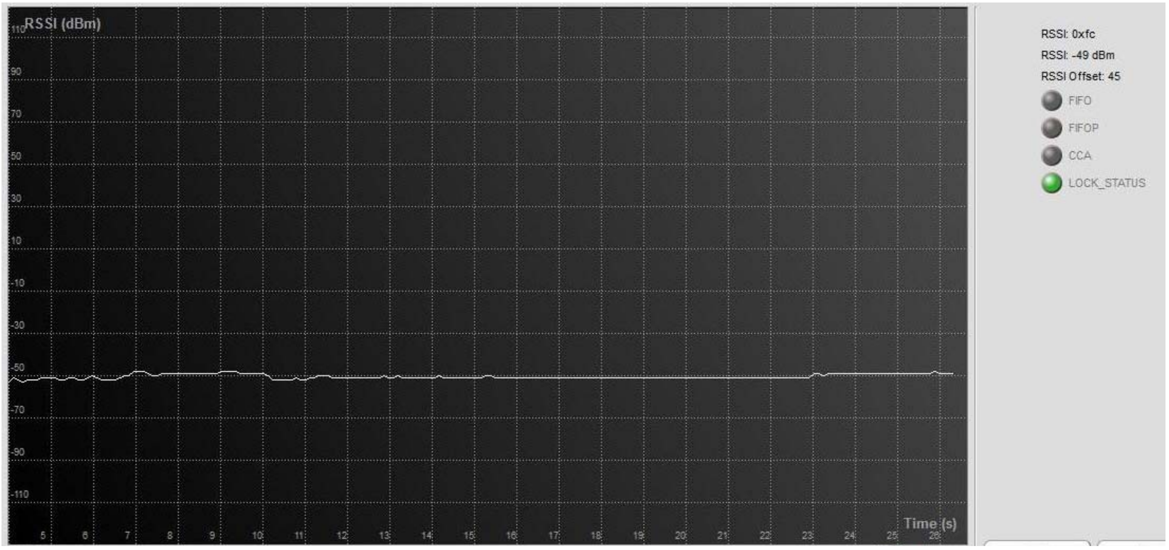


Figure 22 -- Signal Measured by Receiving Tag, Iteration 2

There is no visible difference in signal reception created by the addition of the ABS case. If anything, the signal appears to be stronger when filtered through the case, though this could be the result of minute location movements in constructing the cube. This is good news for our project, as, regardless, the case does not cause any kind of interference.

Home PCB Etching

The reasons behind the decision to use home-etching have already been discussed elsewhere in this paper. Therefore, this section will be restricted to a discussion of the physical process, along with observations on the viability of several steps. The internet is full of many helpful guides to home-etching, although few are detailed or step-by-step. The most helpful of them is written by a man named Alberto Ricci Bitti (please refer to the bibliography), and our process relied heavily upon his advice, though some of it was later proven wrong.

Required Tools

The tools listed below are generally acknowledged by all guides as the required list to accomplish home etching:

- Cheap, but glossy paper (free magazines, advertising brochures)
- A laser printer
- Clothing iron
- Copper clad laminate
- Etching solution

Home-etching works through a relatively simple process. A PCB design is created on a computer, usually using free demo software provided by certain companies or a simple photo-editing program such as Microsoft Paint. This design is printed out onto the cheap, glossy paper using only a laser printer. Laser printers use toner to make an image, not ink, and toner is a kind of plastic, which is resistant to the etching solution. This toner can be transferred to the copper clad using judicious application of heat, such as that produced by a clothing iron. The copper clad with toner PCB-shape on top is then placed in the etching solution. When it is removed, the copper will have been eaten away at every location except those where the toner lies, creating a precise PCB shape. The actual process is quite a bit different from this, and Ricci Bitti suggests several tool additions that will be discussed in detail below, along with the generic process and our experience with it.

Physical Process

The first step in our process is to obtain copper clad laminate. Since much of our purchasing was done early in the semester, when we were still researching exact methods of PCB schematic construction, we decided to buy large boards and cut them down to size as needed. Thus, we purchased several copper clad FR-4, 1/16” thick, 12x12” boards. All of the guides were explicit that such boards could easily be cut—despite the copper and fiberglass layers—by something as simple as a blade cutter and some pressure.

The students would, at this point, like to disabuse this notion. Several hours were spent trying to score and bend the boards to specific lengths. Several attempts were made with hacksaws, pipe cutters, tin shears, and several other implements to cut the copper clad. All failed, in varying degrees or another. A board with deep scores in the main copper layer that has been jaggedly cut or bent, posing a danger to the students' hands, is of no use. Though, the students were unable to get any farther in the process than a few deep scratches and notches in the sides. Eventually, the unmarked copper clad boards were brought to Mr. Breedlove to be cut professionally. He accomplished this with an industrial press of some sort that functioned very similarly to a paper cutter; the board was laid on the edge, and a heavy metal press simply snapped off the pieces laid along the edge. This must be the "pressure" all of the online guides alluded to, though the students do not see how such massive amounts could be accomplished by hand.

The next step that required experimentation is the printing of the finalized PCB design onto the glossy paper. Several guides recommend using high quality gloss photo paper instead of the cheap magazine paper; the students decided to use both. Also, there is only a specific type of magazine paper to be used. The ultra glossy papers in many higher end handouts will not transfer correctly, while the super cheap matte papers common in advertising handouts tear far too easily. Thus, the students looked for a specific kind of paper that was halfway between gloss and matte, and printed the PCB layouts onto those. While the photo paper is thick enough to be printed on alone, the magazine paper should be taped to cardstock first. Otherwise, it is thin enough that it will jam the printer.

All PCB layouts must be printed mirrored, so that when they are transferred, they transfer right side up. This is due to the fact that the paper is laid on top of the copper clad, toner side down; what was once the top of the toner becomes the bottom due to transfer, and the image prints mirrored. Therefore, it must be printed onto the paper mirrored first, so that when it is transferred it is mirrored again into the original image. The students originally had some issues with this property; the software program used to create the PCB layouts did not have a convenient print mirrored option. This could be due to the layout software, or to the print drivers for the printers we were using. Regardless, the original printouts were not made mirrored. This was not an issue for our group, due to the simple parts we used, it was easy to simply rotate the pins and parts to the correct location. If we had more complicated integrated chips with multiple pins, the entire layout would have been messed up; it is impossible to simply rotate such a chip around and have the voltage and ground pins in the right locations.

The next step is to take the pre-cut copper clad laminate and prepare it for transfer. Using normal dish soap and some of the typical green Scotch-Brite pads, clean any grease off of the copper. Handling of the board of any sort puts the typical dirt and grease on our skin onto the copper; this will break up the transfer process. Do not worry if this washing process imprints slight scratches in a circular motion; they are merely cosmetic, and will not damage the future usability. Cut the printed PCB layout down to fit on the board; it is okay if the sizes are not exact. In fact, leaving a bit of space around the edge makes lining up the layout with the board easier. Using tape, attach the paper to the board on one side; make sure that this tape is placed somewhere that there is no toner to be transferred. We tape the paper to the board so that it will not shift during the heat transfer process, but only on one side to make it easy to access the copper underneath.

Bend the paper back, and using the iron set on high, heat up the copper clad. This process should take around 30 seconds to one minute. We heat up the copper first before attempting a transfer to excite the copper and make the bonding process easier to accomplish. This is not a step that can be avoided, as the students discovered; simply laying the paper on top and applying heat does not create a thorough transfer. Once the copper has been heated to the touch, flip the paper back down on top and apply the heat from the iron. Make sure to move the iron over the paper and board, paying particular attention to the locations of the toner.

Figure 23 – Heat Transfer Process

It was at this point in the process that the students discovered another snag in the advice given by the online guides. The high quality photo paper did not take well to being heated. With the iron on the highest setting, the paper immediately bubbled, on the side being heated and on the side with the toner. Many of the bubbles appeared under the toner; when they popped, they distorted the layout's image, and the toner would not transfer no matter how much heat was applied. Although the bubbles only lasted a few seconds, they would appear all across the paper no matter where the heat was originally applied. When the heat on the iron was turned down low enough that the paper did not bubble, the toner would not transfer no matter how long the iron was left on the paper. Thus, the students concluded that in this case, cheaper is better.

Figure 24 – Midway through the Heat Transfer Process

It may take a few minutes to transfer the toner. It is okay to lift the paper up to check if all of the toner has transferred, and to find trouble spots to run the iron over again. The copper will eventually retain too much heat to be touched by human hands; this is a good sign. Once all of the toner has been transferred, lay the paper back down and make one or two more passes with the iron. Do not touch the paper and copper again until the entire set has cooled enough to handle comfortably with bare hands. The paper should be stuck to the copper, and will have to be removed a different way.

Figure 25 – Removal of the Paper

This is another spot in which the cheap paper is preferable to the expensive paper. To remove the paper but leave the heat attached toner, we will soak the now cooled copper in a water bath. When the paper is sufficiently wet, it is safe to scrape the paper off of the copper with fingers. The expensive paper is not soluble in water due to its specific high gloss properties; it would not be easy to simply scratch off once wet. Remove as much paper as possible, including the paper fragments stuck in the toner. Try not to scrub too hard, but the transferred toner is not as delicate as one would think; but avoid the use of fingernails.

Once all of the paper has been removed, the etching process can begin. Ferric chloride, which can be obtained from Radio Shack or made by a knowledgeable student if necessary, especially once it eats away copper, is considered a hazardous material. With the help of a bio-chemistry graduate, the students researched storage, handling, and disposal of the etching solution. The solution has poisonous fumes, so it is best to etch in an outside area; this is why a well-sealed latched cover is necessary for storage. Use gloves and an apron to etch, as the solution stains everything it touches dark brown, and is not exactly something one would want to get on their skin. Once the etching solution has been used, if no hazardous disposal can be found, it is possible to precipitate out the dissolved copper using baking soda. The liquid can then be poured down a sink, much diluted by water, while the copper precipitate must be disposed of properly.

Find an appropriately sized Tupperware container, preferably one with thicker and sturdier sides. A well-sealed, latching top is best for this work, as the etching solution cannot just simply be poured down the sink, as discussed before. Since agitation is required to excite the ions in the solution into attracting the copper off of the board, the container must be deep enough to hold enough solution to cover the board without much splashing. Bring the Tupperware and solution outside, preferably on concrete and near a water hose. Using plastic covered wire, fold/design a holder for the PCB. This holder will be used to dip the copper clad in the etching solution so that hands will not be stained or poisoned. This technique is similar to dying Easter eggs.

Figure 26 – PCB immersed in Etching Solution

Swish the PCB back and forth in the etching solution constantly. Try not to splash too much; this will take quite a while. The guides specify that it should not take too long to etch, but the Radio Shack bottle specifies about 20 minutes. The students' experience confirms this timespan, and includes the news that the more PCBs that are etched in the same solution, the longer this timespan grows. This follows basic chemistry knowledge; the more copper that is dissolved in the solution, the less ions are available to dissolve new copper. Once the copper has begun to dissolve, the rest will dissolve fast. Keep a careful eye on the PCB; we do not want to risk the toner being rubbed off and losing some of the traces.

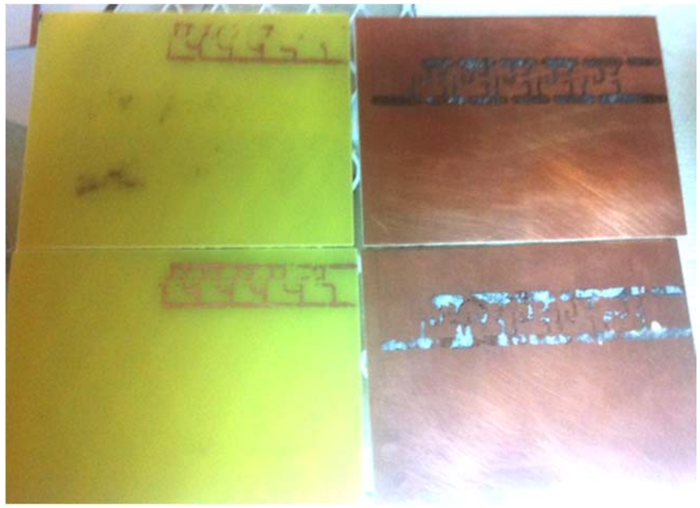


Figure 27 – Fully Etched PCBs next to Un-Etched PCBs

Once all of the copper has been removed, wash the PCB board off with the hose. Remove the toner with acetone (nail polish remover) and a cotton pad. Do not worry about how hard you must scrub to get all of the toner off; the acetone will not remove the copper. When all is said and done, the traces should be, if not perfect, at least usable. Any blank spots where there is no copper can be bridged if necessary, but is best to not have to do this. If the PCBs do not turn out well, the beauty of the home-etching process is that another can always be made.

Hand-Soldering

Now that the PCBs have been etched, it is time to solder them. The students did this by hand, using the equipment available to them on campus. Hand-soldering of SMD components is always tough, particularly for students who do not have much experience with the above. A magnifying glass and steady hands are necessary, as well as specific techniques. One technique that proved useful for the students involved laying solder pads, then reflowing the solder to cover the appropriate pin. Once one pin has been soldered, it is easy enough with a delicate hand to solder the rest. A good pair of tweezers is essential to this technique.

Figure 28 – Soldering the Circuit

There are issues with hand-soldering a home-etched PCB. Many of the SMD components are very tiny, to the point where it can be impossible to solder one pin and not another. The tiny pads needed for the SMD components do not always transfer or etch in the process, and it can be necessary to bridge some gaps. The reverse is also true, in that the small gaps created by the SMD components do not always etch properly, and a knife must be taken to the board to scratch out an appropriate gap. This can create problems with testing of the circuit, although most of the circuits the students soldered did not have any shorts or gaps. This is impressive if one views the size of the components, as in the picture below.

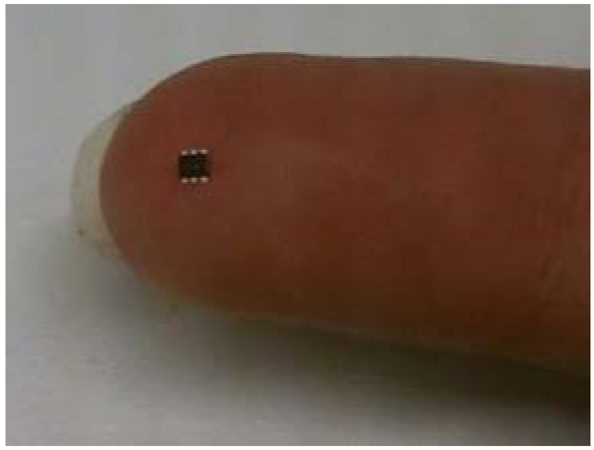


Figure 29 – Size Comparison for One Diode

Timeline

Home-Etching was ideal for our purposes because of the small timeline between conception to implementation and testing. The etching process—once the copper clad boards were cut by Mr. Breedlove and a schematic had already been designed—took about an hour. The more boards there were to etch, the longer the process took; for four boards, it took about three hours. The soldering process took slightly longer, due to the delicate nature of our components and the need for a refresher course. The longest, and most frustrating, portion of the process was designing the schematic to print. This will be touched on in a later section.

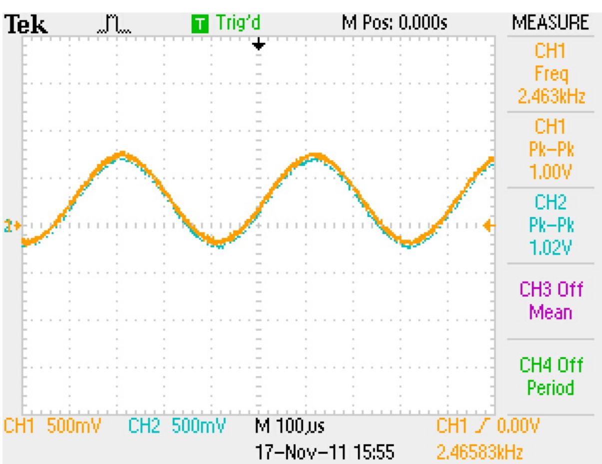
Hardware Performance

Amplifier

Half-Wave

A single stage of a half-wave amplifier has two diodes and two capacitors. Expected behavior is that the more stages there are, the longer the amplifier takes to reach the expected voltage. In addition, there are to be expected slight voltage drops due to the diodes. We etched and soldered two different five stage amplifiers. Amplifier 1 used 100pF capacitors and the BAS40-07 schottky diodes. Amplifier 2 used 1pF capacitors and the 1PS66SB82 schottky diodes. With a $1V_{pk}$ AC sine signal at the input, we should expect slightly less than $5V_{pk}$ at the output. The function generator can only produce signals up to 2.4MHz frequency, which is well below the 900MHz frequency we designed these amplifiers for. However, the decision was made to test these amplifiers at the lower frequency signals due to the successful low frequency spice simulations which did show amplification.

Figure 30 – Amplifier 2



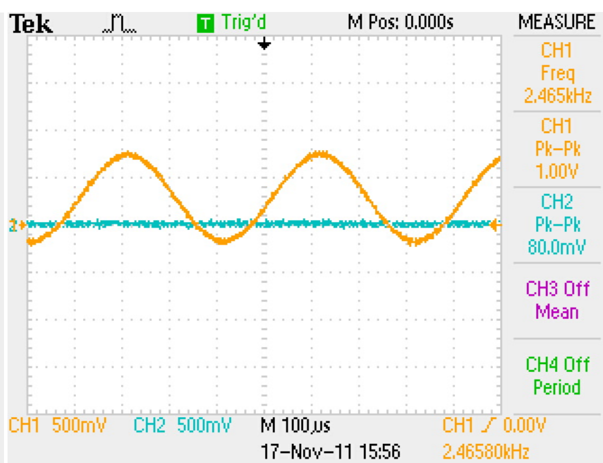


Figure 31 – Amplifier 2 at the input **Figure 32 – Amplifier 2 at the output**

Amplifier 2 did not work at all. The second oscilloscope graph is repeatable across all nodes of the circuit except for the input. This particular amplifier uses the absolutely miniscule

1PS66SB82, so it is certainly possible that one or more of the diodes was soldered incorrectly, and we just cannot tell.

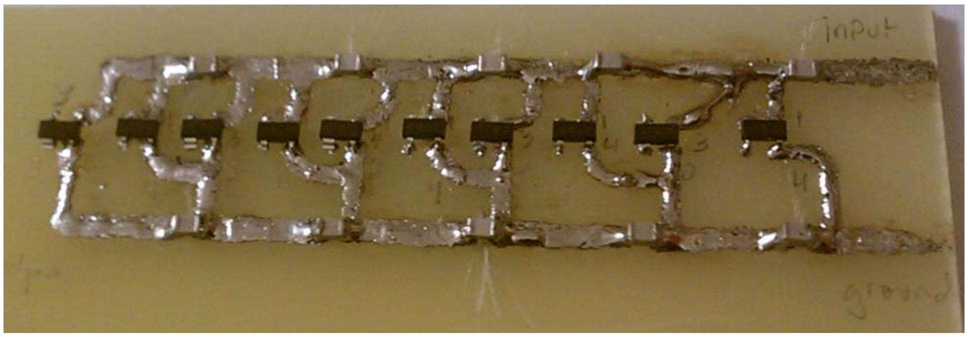


Figure 33 – Amplifier 1

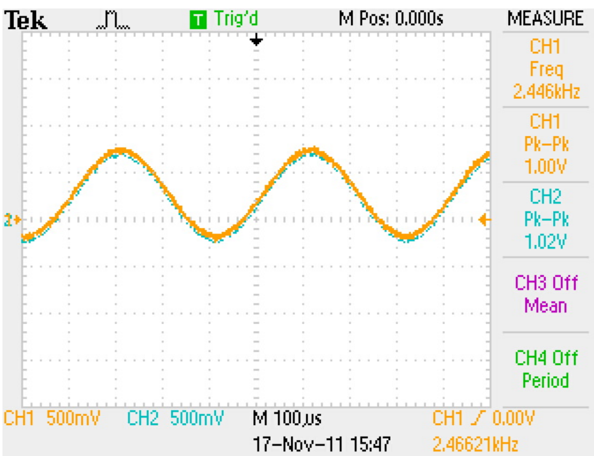


Figure 34 – Amplifier 1 at the input

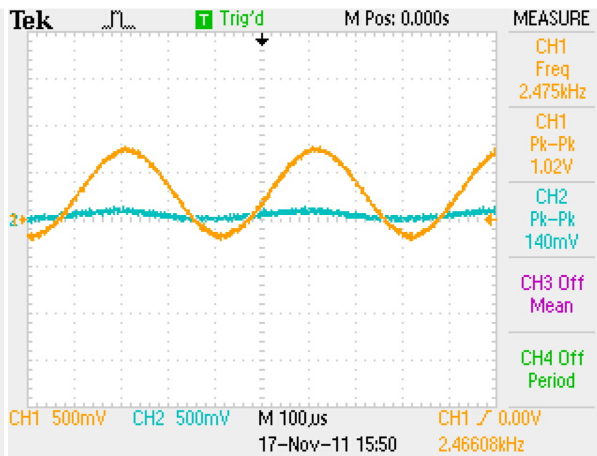


Figure 35 – Amplifier 1 at the output

Amplifier 1 does work, although not the way the students desire. Instead of amplifying the voltage at each stage, it attenuates it. $1V_{pk}$ divided by five, minus some moderate voltage drop for the diodes… would give us around the 150mV at the output we got. The voltage at each stage along the amplifier supports this observation. To visible eyesight, there are no problems with the soldering, and all tests came up positive for working components. Even testing with much lower frequencies ranging from 10Hz to 1kHz to 1MHz did not produce different results. Neither did feeding a larger peak voltage, all the way up to 7V.

Full-Wave

A single stage of a full-wave amplifier has four diodes and three capacitors. Expected behavior is that the more stages there are, the longer the amplifier takes to reach the expected voltage. In addition, there are to be expected slight voltage drops due to the diodes. The behavior of a full-wave amplifier is expected to be slightly different from that of a half-wave; it reduces the ripple at the output and the voltage drop. We etched and soldered three different five stage amplifiers. Amplifier 1 used 100pF capacitors and the BAS40-07 schottky diodes. Amplifier 2 used 1pF capacitors and the BAS40-07 schottky diodes. Amplifier 3 used 100pF capacitors and BAS40-07 schottky diodes, except this time the diodes were soldered with the cathode and anode reversed from the original schematic. Notice that all of the diodes are the same model; this model is much easier to solder than the other, so the students made the executive decision to use only it.

With a $1V_{pk}$ AC sine signal at the input, we should expect slightly less than $5V_{pk}$ at the output. The function generator can only produce signals up to 2.4MHz frequency, which is well below the 900MHz frequency we designed these amplifiers for. However, the decision was made to test these amplifiers at the lower frequency signals due to the successful low frequency spice simulations which did show amplification.

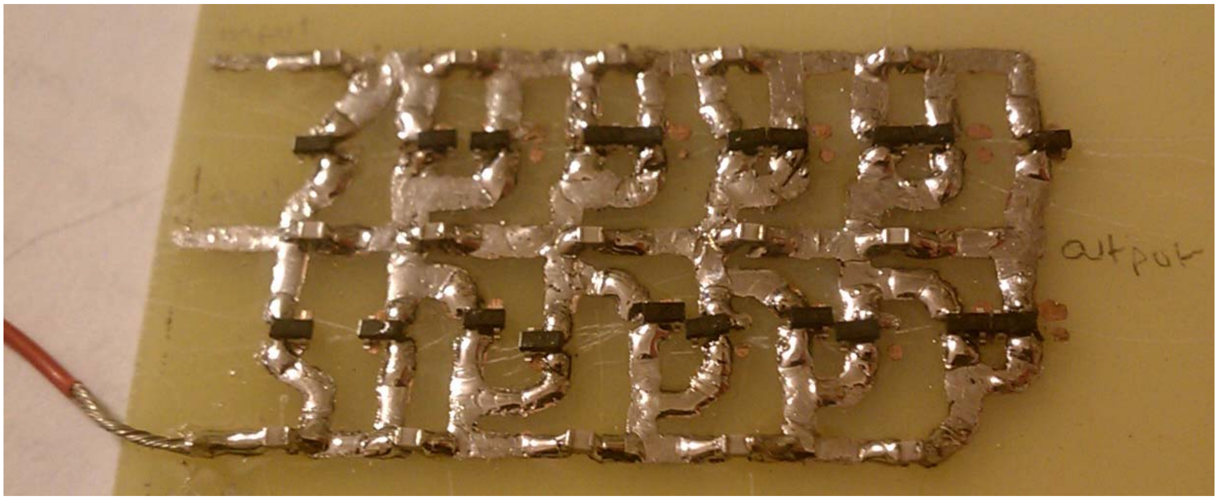
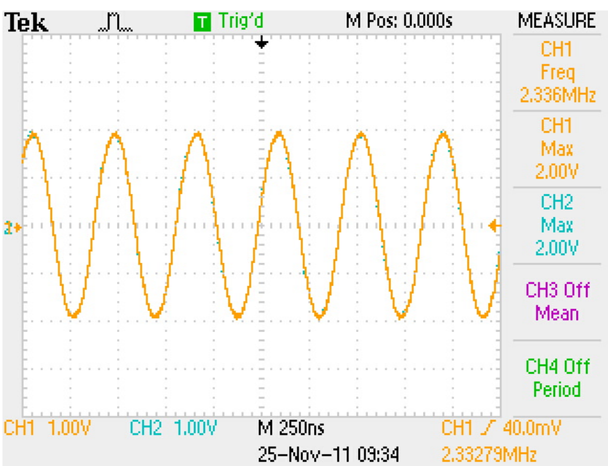


Figure 36 – Amplifier 1



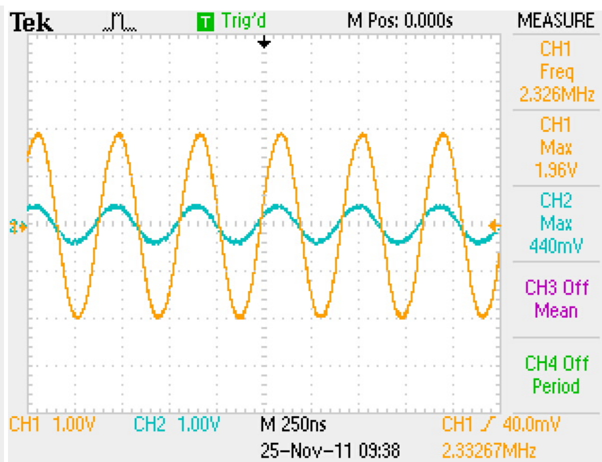
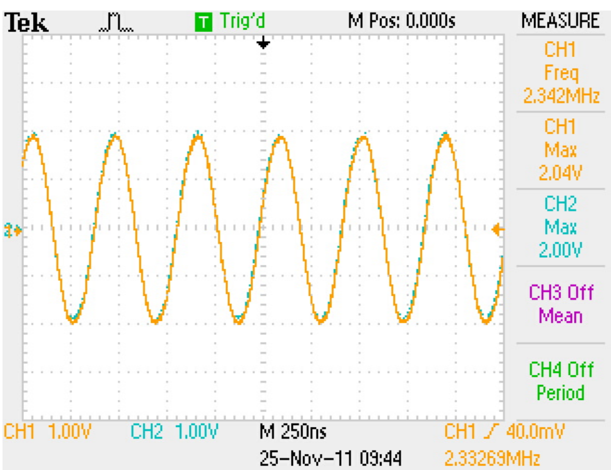


Figure 37 – Amplifier 1 at the input **Figure 38 – Amplifier 1 at the output**

Unfortunately, this amplifier shows the exact same behavior as the half-wave amplifier. A $2V_{pk}$ input is placed at the correct nodes; five stages later, the full-wave attenuates the input to 1/5 its original size. Please note that this amplifier has the same values as the half-wave amplifier that worked similarly, despite the different schematic.

Figure 39 – Amplifier 2



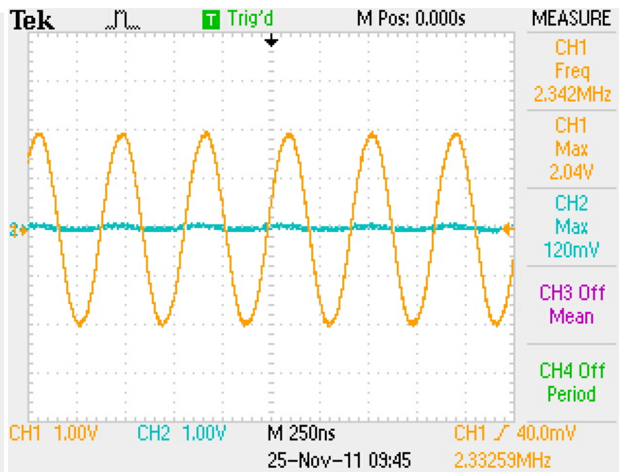
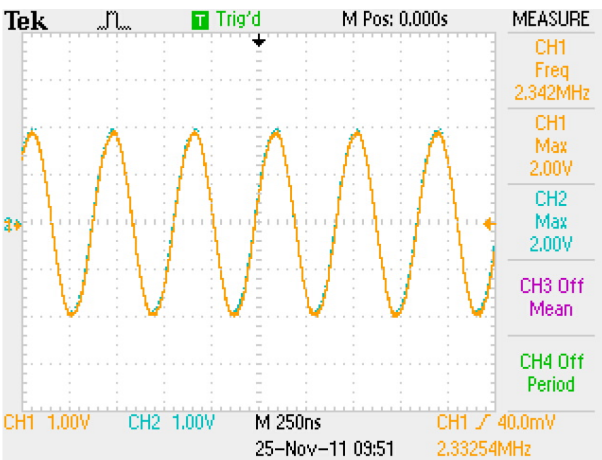


Figure 40 – Amplifier 2 at the input **Figure 41 – Amplifier 2 at the output**

This amplifier directly imitates the half-wave amplifier 2. The voltage at the output is the same on all nodes but the direct inputs. Since we used a different diode this time, with what appears to be good soldering work, we can only assume that it is either the value of the capacitor or the size of the traces that is affecting the operation of the circuit.

In addition, none of these circuits has worked the way we expected. We have extra etched PCBs, and extra components. Just to shake things up, the students decided to solder a circuit with all of the diodes attached backwards.

Figure 42 – Amplifier 3



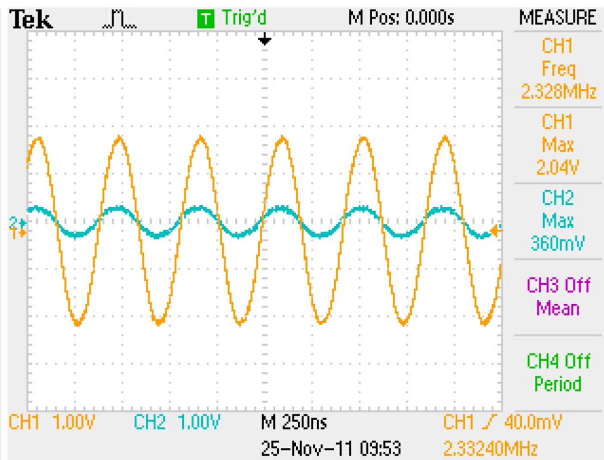


Figure 43 – Amplifier 3 at the input **Figure 44 – Amplifier 3 at the output**

Unfortunately, the tactic did not cause any difference. This is probably due to the fact that the full-wave amplifier is intended to take complete advantage of both the positive and negative peaks of the sine wave. Switching the diodes simply caused the “top” of the PCB to become the bottom, and vice versa.

Conclusion

The question remaining at this point is: do these physical results validate our design decision?

After several attempts of implementing our amplifier with PCB design, we decided to design and implement a amplifier that would work at much lower frequencies on a breadboard. We first used LTspice to build and simulate both a two-stage full wave amplifier and test it at 150kHz on a breadboard in the lab.

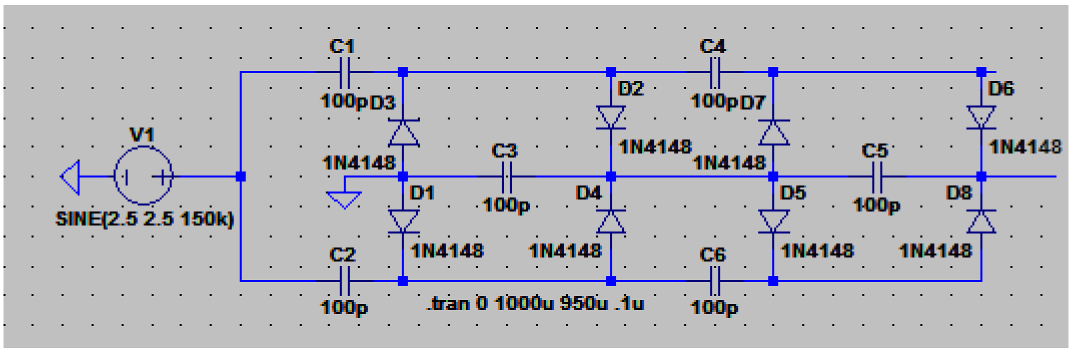


Figure 45 – Two-Stage Full Wave Amplifier in LTspice

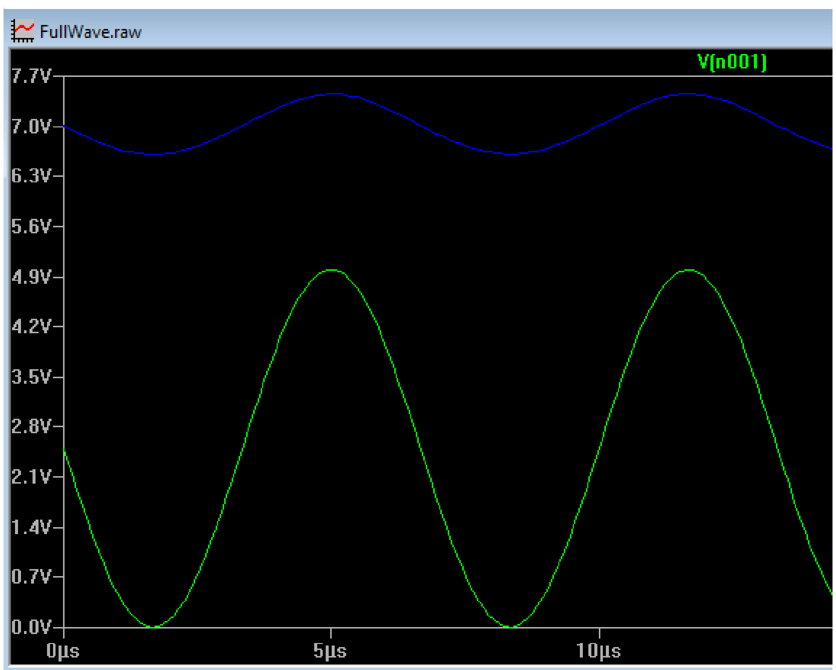


Figure 46 – 5V input sine wave and amplified output

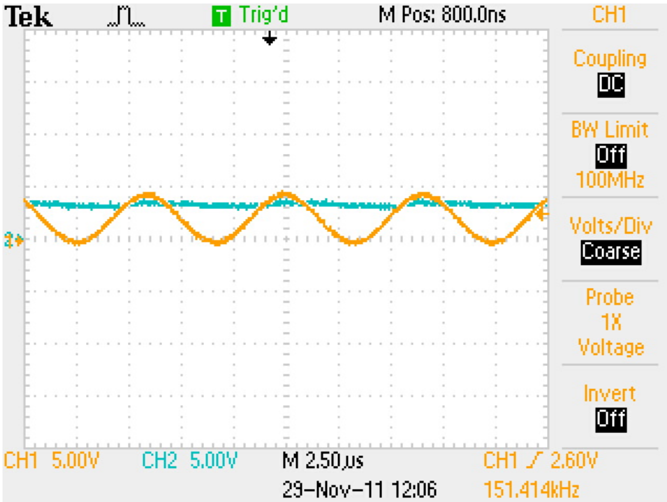


Figure 47 – Stage one lab results

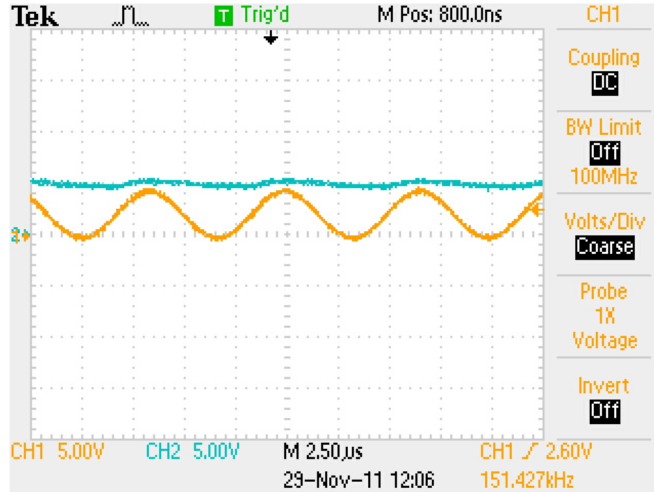


Figure 48 – Stage two lab results

As shown by both the SPICE simulations and the lab test we can see that our design does indeed amplify and rectify. Although we didn't see as much amplification in the lab as we expected by the results we got in our PSPICE simulation, we at least know that it will work if designed correctly on a PCB. This lack of amplification could be due to capacitance induced in the wires even at the relatively low frequencies of 150kHz, as well as losses caused by incomplete matching of the parts we used. Scrounging through the lab for capacitors and diodes to test does not exactly lend itself to matching.

Microcontroller

Prices online of MCU's with the Arduino bootloader already installed are more difficult to find as they are not carried by major retailers such as Digikey, but they can still be found for around $5 per chip which is similar to the price of the AVR chips we originally purchased. Below is a picture of the Arduino UNO with Atmega328 on board attached to a bread board that contains the transistors and LEDs to test and simulate a working circuit.

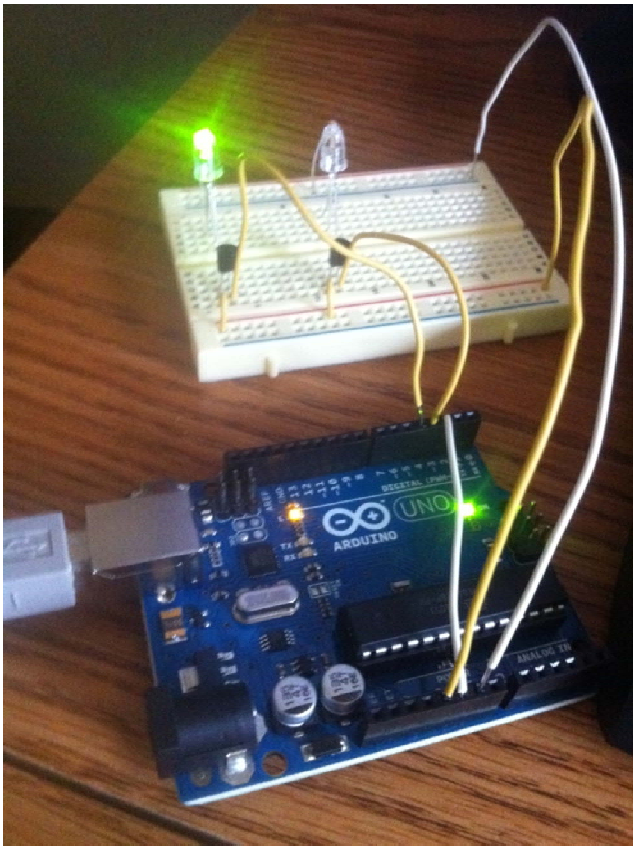


Figure 49 -- Arduino Atmega328P Test

The following paragraph and code explains the logic and syntax for the Atmega programmed with Arduino. However we still have the AVR STK600 kit if the customer wishes to choose to buy AVR chips and program them with AVR studio instead.

The code for this will simply initialize any outputs and inputs we will use on the Atmega and wait for a logic high from the amplifier. Once the input receives a high signal it will send out two signals to two transistors. These transistors will be acting as switches, one for the battery connected to the CC2431 chip, and one for the antenna switch discussed above. We can utilize the antenna switch for an additional purpose as well, to reject any incoming signals for a brief time to prevent the RF tags entering an endless loop of waking each other up. Instead of writing additional code to disable pin inputs/outputs, we can insert an additional delay of about 20-30 seconds after the 5 minute delay and physically reject any incoming signal. The problem lies within being able to implement this antenna switch transistor while not compromising the integrity of the high frequency low power signal. If this switch is to be removed then the code will need to be altered to reject inputs. Neither alteration is too difficult, but any decision on the code to implement will require a decision on design alterations.

Code and Comments

```
const int input = 2;
const int wake_sleep = 3;
const int antenna = 4;

void setup()
{
 pinMode(input, INPUT);
 pinMode(wake_sleep, OUTPUT);
 pinMode(antenna, OUTPUT);
 digitalWrite(antenna, LOW);                  //open antenna switch
 digitalWrite(wake_sleep, LOW);               //wake RFID
}

void loop()
{
 digitalWrite(antenna, HIGH);                 //initialize antenna
 if(digitalRead(input)==HIGH)
 {
  digitalWrite(antenna, LOW);                 //open antenna switch
  digitalWrite(wake_sleep, HIGH);             //wake RFID
  delay(300000);                              //wait 5 minutes
  digitalWrite(wake_sleep, LOW);              //sleep RFID
  delay(30000);                               //wait 30sec
  digitalWrite(antenna, HIGH);                //close antenna switch
 }}
```

Design Challenges

In this section, the students will give a thorough analysis of the challenges and obstacles faced by the team in the attempts to implement the design. This will include a discussion of the challenges faced in simulation, implementation, and testing; or all phases of the process covered this semester. This project was challenging and complicated, and there were many challenges that had to be overcome.

Antenna

In this case, the behavior of the antenna is paramount to our design. The more power we can eke out of a signal reception, the better for our amplifier. But many challenges exist in testing the antennas beyond the tests we have already run. For one thing, the distance results obtained were a bit odd; the signal reception was much lower at close distances than expected given the range. It is possible that the antenna reception would behave differently when faced with an antenna on an actual reader, versus using two different tags.

Aside from this, we were unable to test the antenna attached to the amplifier to see the result. This is partly a fact that our amplifiers did not work, partly that we do not have anything to broadcast through the antenna with at reliable distances and powers, and partly a fact that the amplifiers are designed to work at 900MHz and the antennas only receive at 2.4GHz. 900MHz, SMA “duck” antennas are a relative rarity compared to 2.4GHz, which increases their cost. Their rarity is partly due to their length because of the larger wavelength, and partially because the applications they are typically used for have project-specific in-house antennas made.

Making our own 900MHz antenna has more challenges. The first is matching; to not lose any of the signal, it will need to be matched to 50Ω, which requires some work on Smith Charts and with equations. The other problem is the type of antenna to design; the typical monopole is easy to design, but unwieldy and rather large. It also requires a rather large ground plate, and is rather unfeasible for usage with such small equipment. Other types of antennas either don't have easily available information on how to design for this frequency, or will also be too big. The simple problem is that we ran out of time; so much of this semester was spent on other issues that this one became somewhat of a secondary priority.

Software

Much of the software that deals with radio frequency work is considered highly proprietary; this makes obtaining a license expensive. Additionally, the school does not already own these licenses as the school does not consider them necessary. Therefore, the students immediately ran into problems attempting to simulate their circuits and had to rely upon assumptions. For the expensive programs the students did have access too, such as COMSOL, there was a dearth of information about how exactly to use these programs. When the simulations did not work, the students could not find any help to discover why. The students thus had to rely upon the weight of public opinion, which has both pluses and minuses where engineering design work is concerned. For one, public opinion is often wrong, but for another, there are many credible examples.

The other challenge with software is the high learning curve. Most simulation programs are ridiculously complex, and even with a base understanding it can take many days to figure out how to do something that seems simple. Some of them, such as RF Studio, have detailed user-written guides that provide some help. Some, such as LTSpice and PCB Express, lack the more detailed information. Some barely have any help at all, such as COMSOL. The delays in learning how to use the programs only worsened the other delays experienced by the students. Though occasionally some help could be obtained from other students, this was not enough to overcome some insurmountable difficulties.

PCB Design

LSU does not teach a class in PCB Design, nor is it a common hobby like through-hole electronics. Though sources do exist, they are overwhelmingly aimed at projects that could just as easily use a breadboard, but are intended to last longer. These projects are low-frequency, through-hole affairs, none of which applies to our project. Working with radio frequencies requires a specific set of rules that are both complex and not available in many places. Those guides that do exist are either proprietary guides, non-specific research papers, or hold only one piece of the puzzle. It is the students' opinion that a comprehensive class should be taught on the subject, and a lot of electronic work is done on printed circuit boards. Though much of the information disseminated in such a class would not have applied to this particular project, it would have at least provided a starting point to begin the research from, instead of having to start at zero.

Microwave PCB Design Constrictions

All of the data compiled so neatly below was collected piecemeal over the period of several weeks from many sources, the most important of which are listed in the bibliography for reference purposes. Several of these sources were obtained from an IEEE library subscription, while others were obtained from the ever helpful Google Scholar project, which often lists relevant scholarly papers; one source was the ever helpful Ludwig, Reinhold, and Bogdanov required by LSU's RFID Design class.

There are many, many differences in RF PCB design compared to low frequency design. One of the most major is the tendency of all copper traces at high frequencies to display microstrip behavior, or transmission line behavior. This means that all the rules governing impedance, crosstalk, matching, ground planes, etc come into play. Many of these rules are complex, and different microstrip behavior is needed for different purposes. The first important piece is the parasitic capacitance caused by specific frequencies in specific sized components. We were limited in our choice of frequencies by the components that we could obtain and solder ourselves. After an idea of the frequency is obtained, to minimize distortion and loss of an incoming signal, the impedance of the circuit must be maintained. This involves equations to calculate the characteristic impedance:

$$Z_0 = \frac{87}{\sqrt{\varepsilon_r + 1.41}} * \ln\left(\frac{5.98H}{0.8W + T}\right)$$

Please note that H is the distance from the ground plane to the signal plane, W is the trace width, and T is the thickness of the copper. Using the equations below, we can then calculate the wavelength.

$$V_p = \frac{c}{\sqrt{\varepsilon_{eff}}} \qquad \lambda = \frac{V_p}{f}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\left(1 + 12\frac{H}{W}\right)^{-\frac{1}{2}} + 0.04\left(1 - \frac{W}{H}\right)^2\right]$$

The wavelength generated at 900MHz is too long to be of any use to the students, even with the phase limitation of nλ/2 to maintain impedance. However, the size trace required to maintain the impedance was too big to solder many of our SMD components too. Thus, the students performed some research and discovered something called the critical length. Below this length, impedance control is unnecessary.

C.L. = λ/16 = ~ 8mm

Though this work looks utterly simple summarized in such a manner, lots of research went into piecing it together, and rerunning the equations multiple times. Many weeks were spent pouring over papers, trying to put together a complete enough picture to draw a PCB schematic. So much of our project was based upon assumptions, it was necessary to eliminate as many sources of error as possible. Unfortunately, this pushed back the project a significant amount, a delay that necessitated the use of home-etching and soldering to attempt to make up for lost time. It is the students' hope that all of the research that we conducted in this project, despite setting us back significantly, will be of use to any future iterations.

Home-Etching vs Professional

Though home-etching was the best choice for this group due to the delays, there is nothing saying that it will be the best option for any future iterations or for Cameron

International. There are many drawbacks inherent in the process outside of the actual construction drawbacks discussed previously.

There are many drawbacks to home-etching. The size of the traces and pads that can be accurately transferred are rather large. Most professional companies can accurately etch traces of a far smaller size than those ferric chloride can etch, a plus when trying to stay under the critical length or connect to very tiny SMD pads. In addition, if the heat is applied unevenly, the toner will not transfer accurately or evenly. This is important for small PCB designs; bridging gaps can induce issues, and so can scratching gaps.

Home-etching is stuck with single-layer or double-layer PCB designs, the later being difficult to pull off due to the need for simultaneous heating of both sides. Professional companies can do two-layer and four-layer and beyond boards. Professional boards also come with the traces already tinned, and the boards already treated for long-life. This eliminates the need to do it by hand.

There are drawbacks to professional etching. It is expensive, and there is a large turn-around time. However, this might not be an issue for a group or a project working from our research; the hope is that this research will shorten any delays into an acceptable time period.

Hand-Soldering vs Professional

Though soldering by hand is a classic choice for students, it is not a good choice for a professional manufacturing job. There are companies that will perform this service for a fee, if Cameron does not have the ability to do it themselves. These companies will have the ability to solder the components that the students cannot, making PCB design at 2.4GHz possible.

In addition, the small size (though larger than that required for 2.4GHz), that the students were forced to solder could have caused issues. Though many of the pins appeared correctly soldered, it is possible that some were not, despite tests to the contrary. Many things can go wrong with hand-soldering; excess solder, shorts, open circuits, etc. Professional soldering does not have many of these issues. Occasionally, PCB etching companies also provide professional soldering. There is one such company in Chicago called B.E.S.T (Business Electronics Soldering Technologies) that performs such services in small quantities.

Price

Much of the barriers the students experienced during simulation and testing related to the high cost of the equipment. The high costs worked to make most of the necessary tools simply unavailable, in addition to their rarity because of uncommon usage. Another barrier was the high cost of the components necessary for prototyping. Because these were prototypes, the components were not purchased in bulk, which can decrease the cost drastically. Delivery of parts also surprisingly costs a lot of money, despite the small size of the packages and the option of ground delivery. Perhaps in house development of parts would also lower cost, such as a PCB antenna.

Suggested Final Design

Despite the multiple challenges experienced by the students, much has been accomplished. Though the students did not have the opportunity to test an entire, non-piecemeal wake-up circuit, much of it was proven. The parts that weren't have a very solid background to continue research. Therefore, the students have decided that the final result of the project will be a suggested schematic. Exact PCB design will be left to those with more time, along with our research into do’s and don’ts. There are also alternatives for each suggested part, as deemed necessary.

Schematic

Some parts of this schematic will by necessity be generic. A transistor as part of the amplifier was never chosen, and there are multiple similar options for other parts such as the microcontroller and antenna. There is also a distinct lack of change since the preliminary design review in the battery board, batteries, passive tag and case. The drawing for this is included as a courtesy.

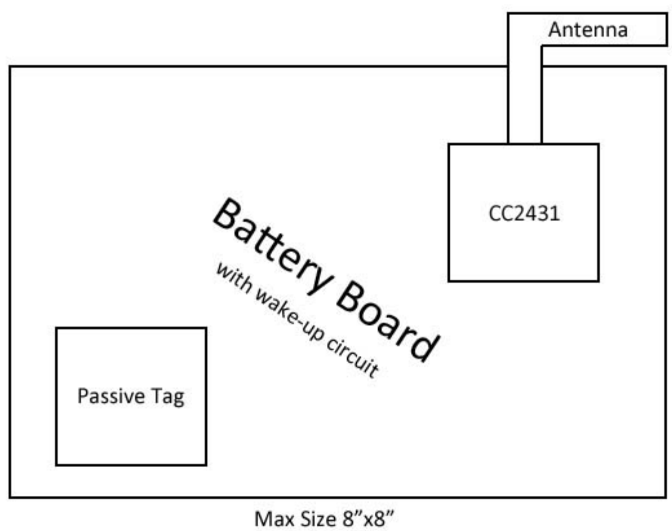


Figure 50 – Suggested Outer Design

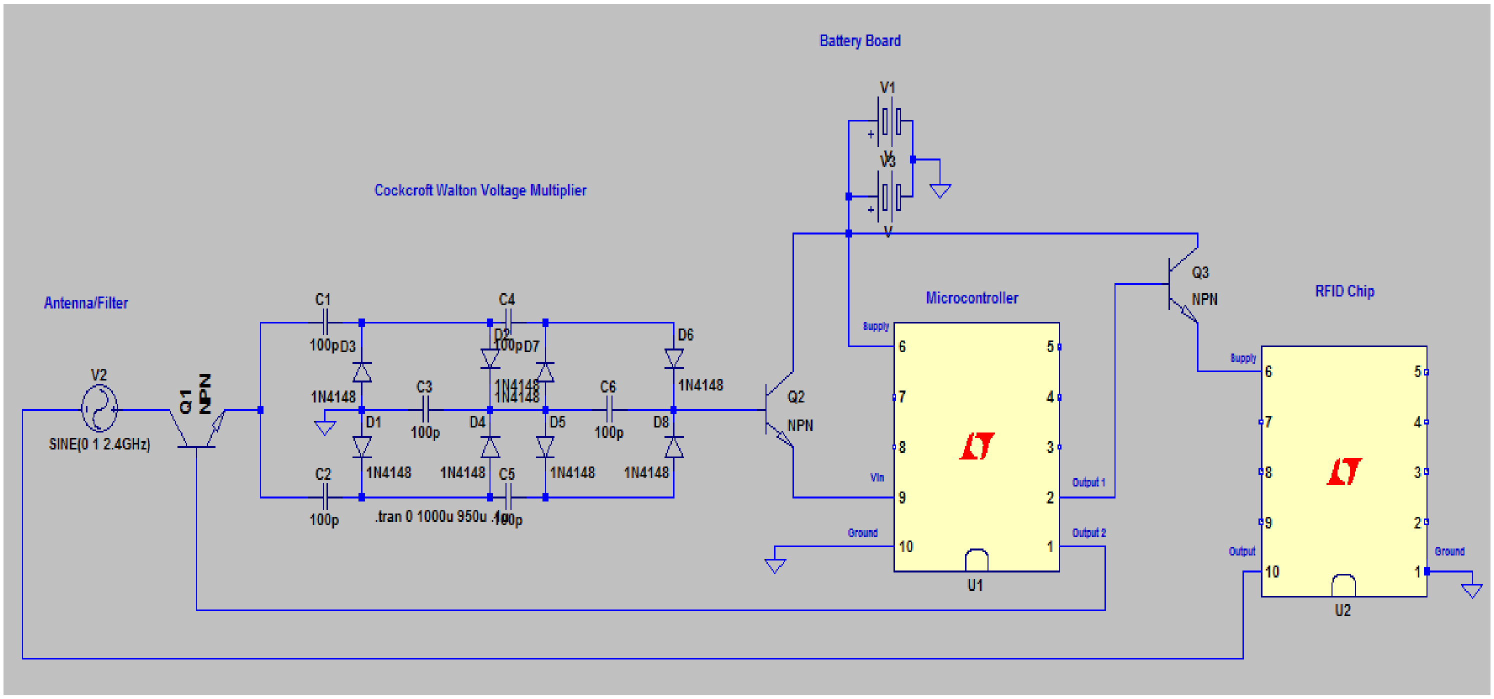


Figure 51 – Suggested Design Schematic

The antenna and filter portion here are represented by a voltage in symbol. This design includes a transistor operating as a logic switch before the amplifier that is controlled by the microcontroller. Since one antenna is connected to both the RF Tag and the amplifier, we should attempt to prevent any loss in transmitted signal by diversion down the amplifier. This switch will trigger at the same time as the switch that controls the power access to the RF Tag. The microcontroller and RF Tag are both generic due to multiple options in their implementation, discussed in a section below.

Service Information

This section covers any necessary knowledge for operation of this circuit. This includes any knowledge necessary for programming the microcontroller, matching the antennas, etc.

The important pieces of this design that must be monitored are the length of times of the on-off cycle in the microcontroller code. The students arbitrarily decided on time lengths; field testing will refine this as necessary. However, this field testing and reprogramming requires knowledge of Arduino microcontrollers. Additionally, there will need to be some method of marking how the antennas are mounted inside of the case, to verify that they are matched as closely as possible. There will also need to be periodic cleaning of the case from any mud or snow to allow for passive tag reading; this works from such a short distance, the interference wrecked could be bad.

Cost Analysis

The prototype costs were high, partially because buying these components in small quantities costs a lot more than buying in bulk. For instance, the 100pF capacitors that we used cost 73¢; if we had bought in bulk, the price would have dropped by 50¢ or more per component. This is only one example; thus we can only provide a cost analysis for how much our prototype cost. Using the—unfortunately misbehaving—five stage full-wave amplifiers as a base, the microcontrollers, and estimates for other parts, our total component cost is:

Table 2: Cost estimate for 5 stage full-wave amplifier

5 Stage Full-Wave Amplifier Tag Cost Estimate		
Component	Unit Price $	Total Price $
Diodes x20	0.246	4.92
Capacitors x15	0.73	10.95
RFID Chip x1	4.16	4.16
Antenna x1	12.00	12.00
Transistors x3	0.033	0.099
Batteries x2	2.85	5.70
Micro Controller x1	5.00	5.00
Total Cost:		42.83

However, something to consider here is the cost of the home-brew versus professional method. Home-brew etching still cost the students money, as we had to pay for copper-clad laminate, soldering supplies, various etching supplies, etc. Professional companies charge per board, plus delivery costs, though the cost does go down in bulk.

Any estimates we make on final tag cost are just that: estimates. They could be wildly off, or right on target. Prototyping is by the nature of the game a relatively high cost endeavor compared to manufacturing, and designs like ours that should be done professionally to cut down on errors… well, each company charges different costs.

Component Alternatives

There are many alternatives to the components in our design that might drive down cost, testing, or size. In some cases, newer, flashier components have arrived since the beginning of this project. Texas Instruments, for example, considers the CC2431 chip we are using obsolete. They suggest upgrading to their new CC2531 chip, which is not simply an upgraded version of the CC2431, despite the name, but has newer technology. The SAW filters we tested were produced by a company called SAWtek, which has since been absorbed into a company known as TriQuint. Their catalog is not available for public perusal, but their company still produces SAW filters; it is a reasonable assumption that they will still be producing similar products to our filters.

There are also alternative antenna choices, most of which involve in house design and construction. Further research into production of a helical antenna is a possibility. There are other, smaller choices that involve integrated chip antennas and PCB antennas. One popular choice for a PCB antenna is called a yagi-uda array.

Alternative amplifiers also exist. There is the op-amp option that the 2010 Capstone Group tried, and several popular options involving transistors. It is the students' believe that the Cockcroft-Walton amplifier is best for the job, and that we ran out of time to prove it.

Hopefully a future iteration or future research will continue along this vein, as our logic is sound, but there are alternatives.

Reader Possibilities

There are many, many commercial readers available. The research and decisions into this have not changed since the preliminary design review. A USB reader is still preferable due to the Augmented Reality portion of the project. There are alternatives, including the BTNode project previously referenced in the preliminary design review; it is easily modifiable to work at any frequency. Please refer to the reference in the bibliography for a refresher.

Lessons Learned

As students, we cannot be expected to know everything going into a design project. Indeed, the Capstone series was invented to give the students practical design experience with all aspects, including challenges, mistakes, and successes. It would not be a proper student experience if there was not analysis of mistakes made, hopefully to prevent the same mistake from being committed in the future. In addition, the documentation of these mistakes can help any future groups attempting to work from our notes. This is demonstrable from the experience of the 2010 Capstone Group. They did not document their research and project as well as they should have, and it led to many problems, both on their part and ours. As such, it was the aim of our group to keep as good of notes as possible. However, there are more current lessons experienced directly by this group, discussed below.

Underestimation of Intensity

Looking at the schematic, it appears nowhere near as complicated as many of the designs involved in our peer's projects. All of the capacitors are the same, all of the diodes are the same, and many of the other components are individual. While it is a simple design and concept, the students underestimated exactly how much research would be required for implementation. The schedules set were based on the assumption that simulation would flow easily into construction and into testing, allowing lots of time for a reiteration of the process.

Better brainstorming or planning could have predicted at least a few of the issues that were encountered by the students. Despite the fact that the students had only ever constructed circuits on breadboards with through-hole components, it was assumed the simplicity of the circuit would lend itself well to construction. More research into construction practices in the preliminary design phase might have helped avoid the time delays. Additionally, the students have discovered the value of easily available information, or the challenge of the lack of it. Rather than simply assuming that there is information available on all subjects freely and easily—as the current technological age has trained us to believe—simple planning would have helped to mitigate the lack of knowledge.

Delivery Delay

The lesson learned here is to never underestimate the unreliability of an inventory; better maintenance is the reason Cameron wants this project, after all. There were many delays caused by incorrect delivery of parts, unavailability of parts that were said to be available, etc.

This happened with reputable dealers such as Digikey and Radio Shack. One way to avoid this is to attempt to have a back-up, in case the first option goes south.

Another thing to pay attention to is the location of the parts warehouse. When ordering parts online, "3-5" days standard delivery does not always mean that. If a delivery is coming from China, for example, it could take two or more weeks to arrive by standard mail.

The biggest lesson learned was to try to never order components for which a datasheet is not provided. If it is the wrong part, then a delay is caused by waiting for it to arrive, realizing it is the wrong part, and then waiting for the new part to arrive. If ordering from a parts warehouse, make sure the manufacturer of the part is easy to find. Often simulation models or more detailed information can be obtained from the manufacturer's website, which can sincerely cut down on simulation time.

Performance Outcome

Goal	Measure of Success	Weight	%	Score
Halfwave Amplifier	Tested at 150kHz worked, unsuccessful on PCB at same frequency	0.25		
Fullwave Amplifier	Unsuccessful on PCB at lower frequency, could not test at designed 2.4GHz, simulations worked.	0.25		
Micro Controller	Successfully Programmed to control switching of transistors	0.25		
Antenna Testing	Antenova Titanis 2.4GHz dipole antenna tested and compared to datasheet	0.0625		
Filter Testing	SAW filters were successfully tested with Titanis antennas, proper bandwidth achieved.	0.0625		
RF Studio Interference Testing	Two CC2431 chips were tested using RF Studio and the effects of interference and distance were observed. Results matched antenna research	0.125		
	Total	1.0		

Conclusion

Overall, we did not achieve the over-arching goal that we set out to accomplish at the beginning of Capstone: to build a complete, working prototype. However we did make significant progress from where the previous group left off. Although we did not get a complete working prototype at our desired frequency of 2.4GHz, we did manage to implement our design on a breadboard at 150kHz and achieve the results that we simulated in LTspice. Given more time and resources we are confident that this can be designed to operate at higher frequencies using the circuit schematic that we designed in **Figure 51**. The two main parts of our circuit, the Cockcroft-Walton Amplifier and micro-controller, are where we made the most progress. A couple things are left that can be improved upon for any group who wishes to take over this project in the future. One of the main things we did not get to test is the antenna and filter working with the rest of our circuit connected. This would allow us to simulate signal degradation through our first transistor to see if it is a viable solution. Also one of the main things we did not get to experiment with is the reader and RFID chip interacting with our complete system. These two areas are where we believe that there is room for the most improvement if this project is to be undertaken in the future. Despite several setbacks we believe our design is theoretically sound and nearly all of it was practically tested in the lab with varying degrees of success.

We'd like to thank the following people for their help in this project: Jacob Luby, Karl Oelschlaeger, Heather McKay, Mr. Scalzo, Mr. Baxter

EE 4820

Final Design Review Part 2

Augmented Reality

Paige Harris and Sam Irving

Fall 2011

Faculty Mentor: John Scalzo, Dr. Jerry Trahan

Industry Advisor: Daniel Baxter

Contents

Introduction

Using the active RFID system developed in the 2010 Capstone Series as a foundation, the aim of this project is to develop an intuitive system for identifying Christmas tree oil well valves in need of maintenance or removal. Ideally, the system will provide an efficient way of doing this without inconveniencing the field technician. The system will be used to hastily identify problematic valves on an oil well tree, which will greatly streamline their maintenance. Presently, valves in the system are labeled with passive RFID tags that can only be read from a few inches away. Technicians must climb the valve trees, which can be up to 20 feet tall, multiple times to access all the passive RFID tags and identify which valve is in need of service. Cameron wishes to replace this with a system that functions entirely from the ground and would allow technicians to precisely identify which valve must be serviced so that they must climb the tree only once. Presently, valve installation records must be accessed manually from Cameron's database to find if a valve is in need of replacement or maintenance. Therefore, it is the goal of our team to create a system that will automate the process of identifying valves on an oil well tree in need of maintenance or removal. This system will be created using a technology called "Augmented Reality".

General Theoretical Design

Basic Overview

"Augmented Reality" is a term used to describe a system that modifies and/or enhances the way reality is perceived. The basis of augmented reality is labeling objects of interest on a real-time video feed. Information being viewed through the AR device's camera feed becomes interactive and digitally manipulable. Our team attempted to utilize AR technology to overlay labels onto a live view of the oil well tree site being streamed through a camera device. These labels will be used to identify valves in need of maintenance or replacement and allow the field technician to identify where the problematic valves are located on the tree itself. This process requires that the computer understand where the valve is physically located in relation to the observer – information which cannot be obtained simply using an RFID system.

Objectives

This Augmented Reality System was not originally part of our overall project's initial specifications, thus true objectives for the system were never officially set. However, the main goal was to provide proof-of-concept for the system. All other objectives were essentially self-imposed in order to achieve said proof-of-concept. Regardless, our group aimed to create and demonstrate that an AR system could be implemented in such a way as to provide a more convenient method of tag identification and tree maintenance. The dynamic determination of each RFID tag's 3D location was another objective that our group received permission to bypass. However, after beginning the implementation of the AR system, it was decided that this dynamic determination was an integral part of what would make the system function as intended and became one of our main focuses in this final semester.

Proposed Design

At the end of the first semester, our group did not have a clear idea of which media was to be used to create our “app”. After receiving confirmation from Cameron that we could focus on Android development specifically, the group had intended to create the app the traditional way using the Android Software Development Kit in combination with Eclipse and an Android emulator. However, it was soon discovered that the Android emulator could not simulate the sensors of the Android phone and thus would not work for our purposes.

Additionally, the existing CC2431 RFID network setup was going to be used to, at minimum, determine the 2D coordinates of the tags. The heights of the tags were to be fixed in the database under the assumption that some extracurricular method was being used to determine it. However, we found that the Z-Location software would not allow us to extract the necessary information and was also highly inaccurate.

Limitations Due to Hardware

Pre-Existing Hardware

The CC2431 platform is a distributed bi-dimensional location finder system that implements the Motorola's IEEE 802.15.4 standard-based radio-location solution exploiting a maximum likelihood estimation algorithm. This means that the accuracy of the system increases with the number of known points around the unknown point. At least 6 known points around the oil well tree would have to be set up as reference nodes in the network in order to get an estimated 2D location that may only be accurate within 3 – 5 meters. Even this accuracy is assuming that the nodes are positioned perfectly so that the antenna signals are projecting towards the node whose position is being determined.

Antennas

The Titanis 2.4 GHz Swivel SMA Antenna used for this project does not have a spherical or symmetrical signal. When using active RFID tags for location finding, the strength of a received signal is used to estimate the distance of the sender. Up to 95% of the signal can be lost in certain antenna orientations, radically decreasing the reliability of the distance finding. Since the main use of the active RFID location finding is locating the user, who is in motion, the inconsistency of signal strength by angle will have a large impact on the accuracy of the system.

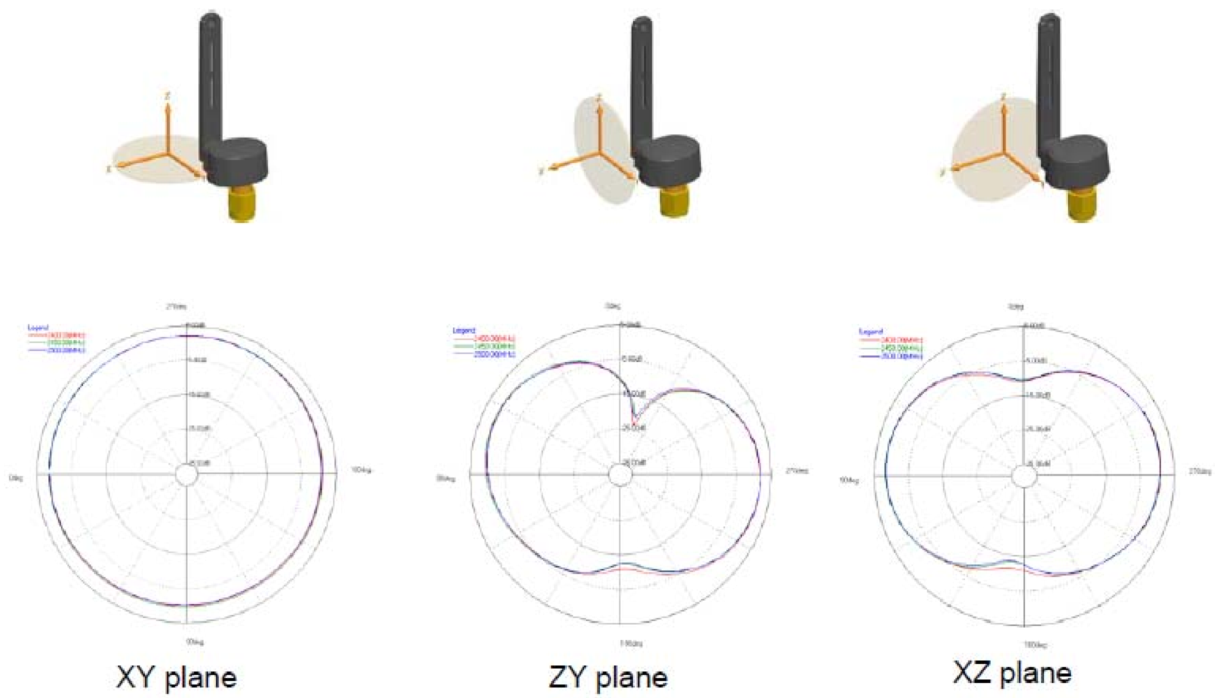


Figure 1: Signal strength of the Antenova Titanis antenna by angle

The above figure shows that the signal strength of the Titanis antenna is largely consistent around the Z axis. This means that distance finding will be most accurate if all RFID tag antennas have their Z-axis in parallel and they are all on the same X-Y plane. The active RFID tag distance finding is only accurate enough to be used in a 2-Dimensional system.

Actual Design

3D Location Propagation

Completed Aspects

Ideal Simulation of 3D Tag Location

A simulation of a virtual system was used to demonstrate what Augmented Reality would look like under ideal circumstances. A laptop was used to manually control the location of the user in relation to a virtual valve tree so that it matched that of a real-life user viewing the tree. This simulation proved that Augmented Reality would be an effective identification tool for technicians.

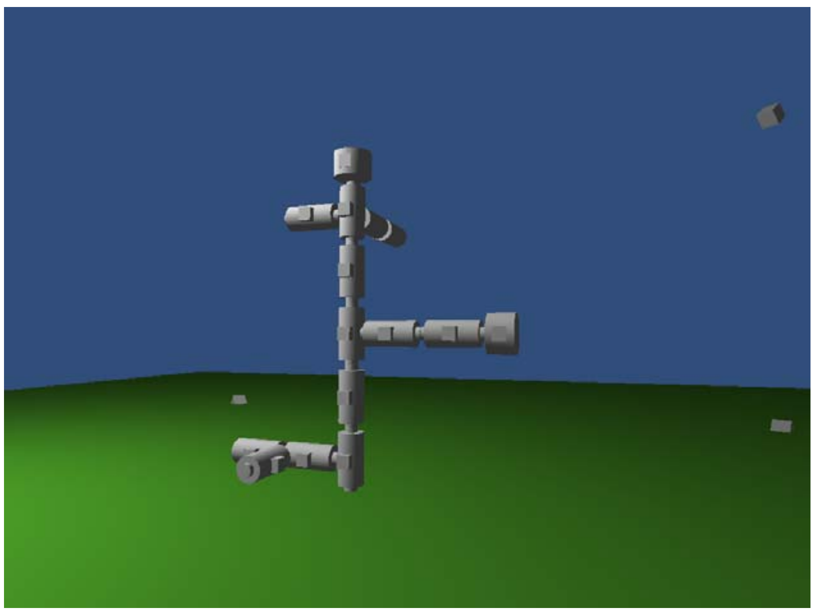


Figure 2: Simulation of Valve Tree used to "perfectly" acquire relative user location

Controlling the user's location manually with a laptop is not practical to be used in the field, but it was useful for demonstrating augmented reality using the actual phone. The 3D valve locations were found manually, so there is no perceivable inaccuracy in the system.

2D Trilateration

The idea behind trilateration is using the distance between multiple known points and an unknown point to narrow the area in which the unknown point may be located. In this method, only the distance between the points is known, giving a circular area around the known point in which the unknown point may be located. The radius of this circular area is the distance between the two points. By adding more and more known points, the possible location area can be narrowed down based on how the circular areas overlap.

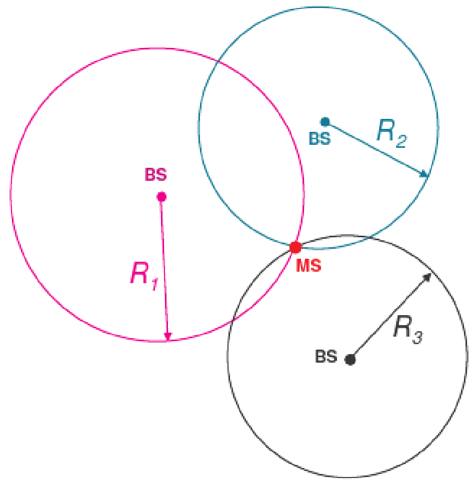
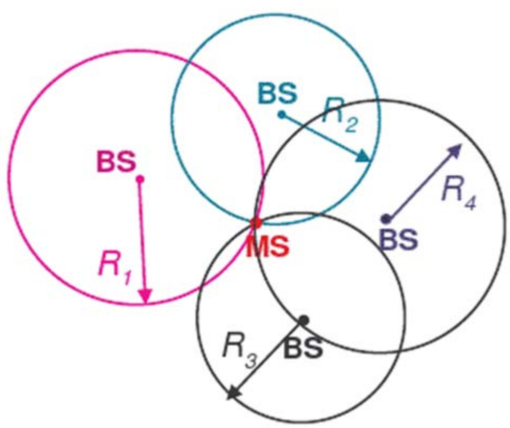


Figure 3: Depiction of 2D trilateration

Performing this technique in 3D requires more known points than 2D trilateration and requires the use of spheres instead of circles.



$$\begin{cases} (x_1 - u_{1,x})^2 + (y_1 - u_{1,y})^2 + (z_1 - u_{1,z})^2 = \hat{d}^2_{1,1} \\ (x_2 - u_{1,x})^2 + (y_2 - u_{1,y})^2 + (z_2 - u_{1,z})^2 = \hat{d}^2_{1,2} \\ (x_3 - u_{1,x})^2 + (y_3 - u_{1,y})^2 + (z_3 - u_{1,z})^2 = \hat{d}^2_{1,3} \\ (x_4 - u_{1,x})^2 + (y_4 - u_{1,y})^2 + (z_4 - u_{1,z})^2 = \hat{d}^2_{1,4} \end{cases}$$

Figure 4: Two-dimensional representation of 3D trilateration with equations

The most accurate way of measuring blind active RFID tag locations is using 2D trilateration. Using three static tags surrounding the tree, we were able to find the 2D position of the user in relation to the tree. However, for trilateration to work, the static and blind nodes must all be at the same height off the ground. This means that the static tags must be elevated off the ground and that the user must be wary of how he is holding the phone. Maintaining constant elevation circumvents the impact of the blind spot in the antenna, and makes Augmented Reality actually usable. The inaccuracy of the system varied, but was within 3 feet.

Simulation of Theoretical 3D Tag Location

An equation for the signal strength of the Titanis antenna was found, and the field was simulated to test the accuracy of quadrangulation different active RFID tag orientations.

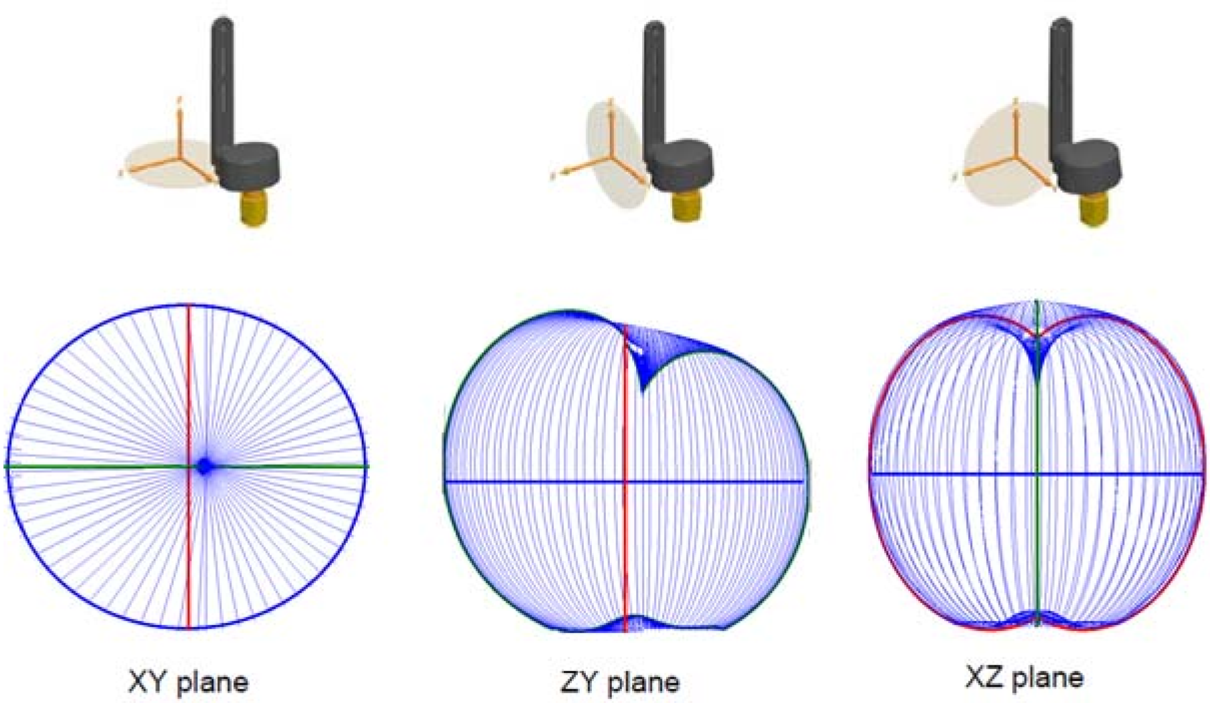


Figure 5: Dipole antenna signal strength by angle from official specifications (top) and project simulation (bottom)

Using simulations of the active RFID tags, a simulation of quadrangulation was performed.

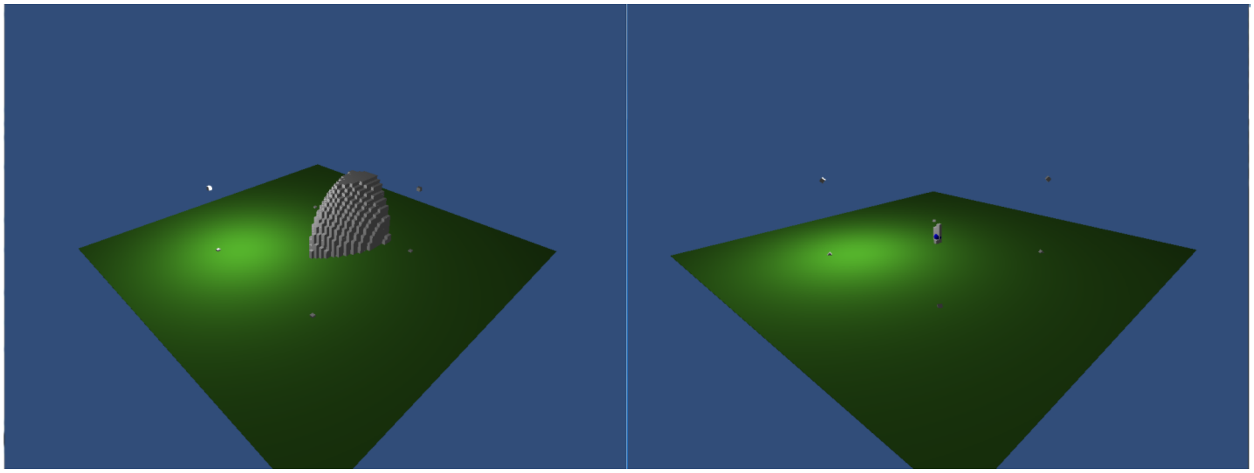


Figure 6: Simulation of Quadrangulation ignoring tag orientation (left) and with ideal tag orientation (right)

In the simulation, a blue orb was used to represent a “blind” active RFID tag, or a tag whose location is not known. The blue orb was surrounded by 6 grey cubes, representing static active RFID tags whose locations are known. The strength of the signal from the blue tag received by each static tag is used to estimate a maximum distance between the two. Using these six distances, the possible locations for the blind node were calculated and are rendered as a mass of grey cubes, each representing .5 cubic feet.

A first simulation was conducted with all static active RFID tag antennas positioned with the blind spot pointed upwards, which is likely how a technician would place the tag. The simulation showed that using six static tags for quadrangulation would not be accurate enough if they are oriented arbitrarily. Actual quadrangulation would say the blind node was located at the average of all possible locations. The first simulation yielded a location that was about 7 feet away from the actual location.

A second simulation was conducted with the most spherical portion of the antennas signal strength pointed inwards. With these ideal antenna orientations, the accuracy of the system is much higher, with the simulated quadrangulation reported a location within a foot of the actual location. However, it is unrealistic to think the tags could be properly oriented in the field by technicians. Since the tags are not perfectly consistent, the accuracy of the system gets exponentially worse as the user moves away from the center of the six static RFID tags.

Incomplete Aspects

Fixed Location, 2D Trilateration

2D Trilateration could be used effectively if there were preset locations encircling the tree. The trilateration would be used to find which location the user was closest too, and report to the database that the user is standing exactly at the pre-set location. The user would have to walk until he is standing in the designated location, or the labels will not be in focus. Having the triangulated user location "round" to the nearest preset, fixed location is the simplest way to ensure that Augmented Reality is accurate and functional.

Quadrangulation

Due to the asymmetry of the dipole antenna used in this project, locating active RFID tags in 3D is too inaccurate to be practical. An antenna with a signal strength that does not vary by angle is needed to produce the accuracy required of Augmented Reality for use with close proximity valves.

Multiple Tag Arrangements

An ideal antenna with a perfectly spherical signal could perhaps eliminate the need for statically placed tags surrounding the tree. Just using the distances between each tag fixed to the tree, a model of the valve tree could be created, though it would not be properly oriented with respect to ground or north. Metal interference would pose a major problem to the "internal" 3D locating system that was eliminated using the "external" trilateration.

Database

All technicians will need to access the database through an active Internet connection. Connecting to and updating the database was essential for the success of this project. The database must be updated after each reading of the tree. After the reader scans all tags actively transmitting their RFIDs, it must update the database with a list of the tags found in relation to the current tree. Then, the AR device will access the database using this list of tags and display data associated with each tag ID. It is very important for this information to be kept up-to-date and accurate so that technicians utilizing our system can make well-based decisions on the maintenance or replacement needs of any existing valve and its corresponding active RFID tag.

Cameron instructed our group to spend minimum time developing and designing a database as the company itself already has its own database that will be integrated with the project's final product. However, to test and implement our system, we modeled the interaction between our program and a database. To do so, a server owned by a member of the software team hosted the MySQL database we used for the project and housed all information in the form of tables.

Completed Aspects

Server

The PHP scripts and MySQL database were hosted in GoDaddy server. The scripts were accessed through the temporary URL: http://www.sam-irving.com/. The server was used primarily to test the connection speed between a worst-possible-case economy server and a smart phone using a data connection. The speed was consistently fast enough for Augmented Reality.

PHP Access Scripts

The cell phone accesses the database by opening different PHP scripts hosted on the server. There is a different PHP script for each set of data the user may want to access. The PHP side simply accepts HTML's FORM input which a browser can send in. Variables, such as the ID of an active RFID tag, are passed through the URL when accessing the script.

For example:

http://www.myHost.com/PHPScript.php?ID=1234

The script then makes a MySQL query using the variable, and prints out relevant data as plain text. This plain text is interpreted by a java script running on the phone and converted into information the user can understand. PHP is a safe way to approach this because it is easily restricted. Additionally, if the code from Unity were to ever be made public, people would be unable to see passwords for access to the database and would also be unable to alter the code and corrupt it.

Incomplete Aspects

PHP Edit Scripts

Scripts similar to the access scripts can be used to edit the database directly from the phone, but this was not attempted for this project. It is possible to create a touch interface on the smart phone where the user can designated a field in the database to edit and upload information, such as a sentence explaining the status of a valve, but this was unnecessary to prove the concept of augmented reality. PHP scripts that can edit the database also required a higher level of security than was used for this project.

Security

In this demo, there is virtually no database security. All PHP scripts can be accessed knowing the server address and the name of the script. This means that database information could be viewed by anonymous browsers, but it cannot be edited. Since no real information was inserted into the database, security was not deemed necessary.

App Front End

Completed Aspects

Unity 3D App for Android

The Unity 3D development platform was used to produce all PC executable demos and smart phone applications. Unity has a built in 3D engine and can export directly to PC, iOS and Android with minimal user effort. Unity also supports multiple languages and has built in libraries for connecting to the internet. There was a great deal of difficulty getting Unity to access some of the Android's built in hardware, but ultimately Unity streamlined the process of creating demonstrations, simulations and adding polish to the application.

Camera Background

A Unity plugin was written to access the smart phone's camera and convert it to a 2D texture rendered behind the 3D valve labels. Though Augmented Reality by definition is modifying our perception of reality so we have access to more information, having the camera enabled at times was found to drastically reduce the battery life of the phone. A feature could be added to allow users to enable or disable the camera, but presently the camera is disabled. A virtual valve tree was instead used for the background to reduce inaccuracies of the 3D locating system.

Real Menus

Functional menus that pull information from the database were created to demonstrate the benefits of using Augmented Reality. When a valve is tapped on the smart phone screen, its RFID tag number is used to query the database and pull relevant information. The menus used in the demonstration would likely be totally redesigned to display information from sensors not included in our project, or other information Cameron technicians consider most important.

Incomplete Aspects

Additional Menus

From the augmented reality real-time display, the user should be able to touch the labels of highlighted RFID tags and continue into a valve-specific menu. From this menu the user will view valve related information from the database. There should be menus for all relevant information. All information related to the operation of the valve should be viewable in a form on the tag selection menu. This information should include the serial number, the RFID numbers, the battery life, date of last maintenance, installation date, last date the RFID was scanned, and any other values desired by Cameron.

Any alerts created by the system should also be displayed list-style in the tag selection menu. The user would, ideally, be able to override these alerts and dismiss them if they have been resolved, and also be able to create custom alerts and associate them with the valve if other technicians must be alerted to the status of the valve.

Cameron specifically requested that the system support further sensor addition. The method of displaying the values associated with each valve in the graphical user interface must lend itself towards adding additional fields in the future.

From the tag selection menu, the user should also be able to select a maintenance history of each valve. From this list, the user would see a record of each value that has been changed, recently dismissed alerts, and an RFID tag location history.

We also wanted to give the option of circumventing the use of the augmented reality system entirely by searching through valves in the area. The user would be able to search using criteria such as serial number, expiration date, passive RFID, active RFID tag, and tree associated with the tag.

Port to iPhone

A major advantage to using Unity 3D as a development platform is that it can export to both iOS and Android OS. Scripts for accessing the phone's hardware will have to be changed, but all code for accessing the database and displaying tag labels can be ported directly.

App Back End

Completed Aspects

Accelerometer

The accelerometer built into the Android smart phone was used to find the pitch and roll at which the phone is being held. By finding the direction of the force applied by gravity, the phones orientation with respect to ground can be found. Unfortunately, the accelerometer will detect any force on the phone, which may mask the true direction of gravity. If the accelerometer does not have a perfect magnitude of $9.8\ m/s^2$ it is not possible to know the rotation of the phone without additional sensors. The accelerometer is known to be heavily disturbed by motions as slight as trembling fingers. Much work was done to reduce the effects of shaking while holding the phone and keep the measured angles stable.

Unity 3D Plug-in: Compass and Gyroscope

Unity 3D does not natively support the compass or gyroscope sensors. A Unity plugin was written in JavaScript to make all of the phone's sensors available. The Android operating system includes linear acceleration, orientation, and rotation "virtual sensors" that are actually just built-in calculations using the accelerometer and compass. Access to these additional sensors was added via Unity plugin, but they were found to be too inaccurate to be useful. The compass, or "magneto-sensor," is vulnerable to interference, and will sometimes shake slightly despite the phone being stationary.

Gyroscope Correction

A gyroscope can be used to detect the Android's rotational acceleration, and significantly less impacted by shaking. The gyroscope can be used to find the rotation of the phone, even if the accelerometer is detecting more than just the force of gravity. The gyroscope readings are used to estimate the phones orientation when the accelerometer senses that the phone is in motion, such as when the phone is shaking slightly in place. The addition of a gyroscope can greatly improve how steady the Augmented Reality labels are. An HTC EVO 3D with a built in gyroscope was specially purchased for this project, as gyroscopes are not yet common in Androids. All scripts will run on phones with or without a built in gyroscope.

Inertial Navigation System

The phone's 3D displacement can be found knowing an initial starting location and the phones acceleration. Using active RFID tags to find the phone's absolute location and transmitting it through the database takes a brief, inconsistent amount of time. In between updates, an inertial navigation system can be used to track the phones location. The inertial navigation system's accuracy will decrease exponentially the longer it is used, but is needed if the Augmented Reality user is in motion.

Tree-Growing System

To minimize the inaccuracy of the 3D location measurements and the phone's orientation measurements, all active RFID tag locations were measured in relation a "base" node. The "base" node is the active RFID tag that is at the exact origin of the system. Since the tree is in a static location, active RFID tags do not need to be used to find the valve locations after installation. The values in the database are used by the phone to produce a skeleton of what the tree looks like. The skeleton label removes the labeling ambiguity seen when using simple, spherical labels.

Figure 7. Rendering of simulated valve tree and matching "grown" skeleton

Incomplete Aspects

Full Gyroscope Correction

The stability of the phone's measured orientation was deemed to be good enough for proving Augmented Reality is possible, but stands to be improved. Not all spontaneous jerks in the phone's rotation were eliminated from the accelerometer and gyroscope readings due to time constraints.

Inertial Navigation System

The inertial navigation system is heavily dependent on having an accurate orientation of the phone. The rotation must be known so that the force of gravity can be eliminated from the accelerometer's readings, producing an estimation of the phone's linear acceleration. Any jerks in the phone's orientation will cause the inertial navigation system to drift out of place. As the orientation was never perfectly stabilized, the inertial navigation system was deactivated for the final demonstration.

Tree-Growing System Correction

The tree growing system implemented in the application can be used to correct inaccuracy in the measurements of the 3D RFID tag locations. This was not explored beyond adjusting tag locations so that they formed straight trunks or branches where appropriate. Alternatively, the skeleton produced by the tree growing system could be manually corrected by a technician so that it perfectly matched the tree.

Tree Recognition

The skeleton produced by the tree growing system could be used, in conjunction with the phone's GPS and compass, to recognize the shape of a valve tree. The phone can know which tree is nearby, which direction it is facing and what the skeleton of the tree looks like from that direction. Making shape recognition was beyond the scope of this project, but could be implemented to improve accuracy.

Phone Battery Life Consideration

The combination of running Unity 3D, accessing the camera, and maintaining a constant internet connection can run out the battery of an HTC EVO 3D in about 30 minutes. As the purpose of this project was to prove the concept of Augmented Reality, this was not really considered an issue. Improvements in Unity's built in 3D rendering engine, the Android's operating system, and smart phone hardware will improve the battery life of the Augmented Reality application.

Conclusion

For this project, we explored multiple methods of creating an Augmented Reality system using active RFID tags. We proved that making such a system is possible and that it would be an effective tool for inventory maintenance. Shortcomings in hardware prevented the locating of 3D tags from being as robust as desired, but we found was of mitigating the inaccuracies. There is still much to be done before the perfect Augmented Reality application is produced, but this project took the first big step in exploring how it could be done and just how useful it could be.

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